NASA/TM—2015–218201

# Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report

*C.M. Crumbly and F.P. Bickley*
*Marshall Space Flight Center, Huntsville, Alabama*

*U. Hueter*
*Jacobs ESSSA Group, Marshall Space Flight Center, Huntsville, Alabama*

***January 2015***

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National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

***January 2015***

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## LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

| | |
|---|---|
| ABEDRR | Advanced Booster Engineering Demonstration/Development and Risk Reduction |
| ADG | Advanced Development Group |
| ADO | Advanced Development Office |
| AE | acoustic emission; augmented expander |
| AFRL | Air Force Research Laboratory |
| Ag | silver |
| Al | aluminum |
| ALD | atomic layer deposition |
| $Al_2O_3$ | aluminum oxide |
| AM | additive manufacturing |
| AMRDEC | Aviation and Missile Research Development and Engineering Center |
| Ar | argon |
| ARC | Ames Research Center (NASA) |
| ATP | authority to proceed |
| AUSE | advanced/affordable upper stage engine |
| AUSEP | Advanced/Affordable Upper Stage Engine program |
| BT | barium titanate |
| C | carbon |
| CDR | Critical Design Review |
| CE | Chief Engineer |
| CFD | computational fluid dynamics |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| COTR | contracting officer’s technical representative |
| CPS | cryogenic propellant stage |
| CPST | Cryogenic Propellant Storage and Transfer |
| CSO | chief safety officer |
| CT | computed tomography |

## LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

| | |
|---|---|
| CTS | composite tank set |
| CWN | channel wall nozzle |
| DCR | Design Certification Review |
| DDT&E | design, development, test, and evaluation |
| DESLA | dual-expander, short-length aerospike |
| DoD | Department of Defense |
| ED | Engineering Directorate |
| EDM | electro-discharge machining |
| EDRR | engineering development risk reduction |
| EELV | evolved expendable launch vehicle |
| EM10 | Materials Test Branch |
| EMA | electromechanical actuator |
| ER43 | Propulsion Systems Department |
| ESD | Exploration Systems Development |
| EUS | exploration upper stage |
| FOM | figure of merit |
| FSI | Foam Supplies Incorporated |
| FSW | friction stir weld/welding |
| FTBV | fuel turbine bypass valve |
| FWC | filament wound case |
| FY | fiscal year |
| Gen | generation |
| GG | gas generator |
| GN&C | guidance, navigation, and control |
| GWP | Global Warming Potential (rating) |
| $H_2$ | hydrogen |
| HCB | hydrocarbon boost |
| HEA | heat exchange assembly |
| HFO | hydrofluoroolefin |
| HIP | hot isostatic press |

## LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

| | |
|---|---|
| HM | health management |
| HPCL | High-Pressure Combustion Lab |
| HTPB | hydroxyl terminated polybutadiene |
| HTPE | hydroxyl terminated polyether |
| ICE | internal combustion engine |
| ICPS | Interim Cryogenic Propulsion Stage |
| IRT | infrared flash thermography |
| Isp | specific impulse |
| ITAR | International Traffic in Arms Regulations |
| IVF | integrated vehicle fluids |
| KCl | potassium chlorine |
| KF-EPDM | Kevlar-filled ethylene propylene diene monomer |
| LBM | Lattice Boltzmann Method |
| LEO | low-Earth orbit |
| LES | large eddy simulation |
| $LH_2$ | liquid hydrogen |
| $LN_2$ | liquid nitrogen |
| LOX | liquid oxygen |
| LPFP | low-pressure fuel pump |
| LPOP | low-pressure oxidizer pump |
| LPT | Lagrangian particle tracking |
| LSGS | Line Symmetric Gauss – Seidel |
| MCC | main combustion chamber |
| MFV | main fuel valve |
| MOV | main oxidizer valve |
| MPI | messaging passing interface |
| MPS | Main Propulsion System |
| MRCV | mixture ratio control valve |
| NDE | nondestructive evaluation |
| NESC | NASA Engineering and Safety Center |

## LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

| | |
|---|---|
| NGAS | Northrop Grumman Aerospace Systems |
| NGE | next generation engine |
| NRA | NASA Research Announcement |
| O | oxygen |
| OD | outside diameter |
| OLDAC | Outer Loop Design Analysis Cycle |
| OOA | out of autoclave |
| ORNL | Oak Ridge National Laboratory |
| ORSC | oxygen-/oxidizer-rich staged combustion |
| OTBV | oxidizer turbine bypass valve |
| PAUT | phased array ultrasonic technology |
| PBI-NBR | polybenzimidazole-nitrile butadiene rubber |
| Pc | pressure chamber |
| PCO | carbon monoxide partial pressure |
| PDR | Preliminary Design Review |
| PDS | Production Development System |
| pmf | propellent mass factor |
| PI | principal investigator |
| PLI | propellant liner insulation |
| PM | program manager |
| POD | probability of detection; point of departure |
| PP&C | Program Planning and Control |
| Pr | Prandtl Number |
| PSD | power spectral density |
| PWR | Pratt & Whitney Rocketdyne |
| RANS | Reynolds-averaged Navier Stokes |
| Re | Reynolds Number |
| RMS | root mean square |
| ROCETS | Rocket Engine Transient Simulator |
| RP | rocket propellant (kerosene) |

## LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

| | |
|---|---|
| RTR | real-time radiography |
| SBKDF | shell-buckling knockdown factor |
| SC | staged combustion |
| Se | selenium |
| SEM | Systems Engineering Management |
| SEMP | Systems Engineering Management Plan |
| SLM | selective laser melting |
| SLS | Space Launch System |
| SPIE | Spacecraft/Payload Integration and Evolution |
| SRB | solid rocket booster |
| SR-FSW | self-reacting, friction stir weld |
| SRM | solid rocket motor |
| SRR | System Requirements Review |
| SSFC | supersonic film cooling |
| TCA | thrust chamber assembly |
| TEA | triethylaluminum |
| TEB | triethylborane |
| Ti | titanium |
| TIM | Technical Interchange Meeting |
| TM | technical monitor |
| TPA | turbopump assembly |
| TRL | Technology Readiness Level |
| TRR | Test Readiness Review |
| TVC | thrust vector control |
| ULA | United Launch Alliance |
| USAF | United States Air Force |
| USET | upper stage engine technology |
| V | vanadium |
| W | tungsten |
| XRD | x-ray diffraction |
| Zn | zinc |

TECHNICAL MEMORANDUM

# SPACE LAUNCH SYSTEM SPACECRAFT/PAYLOADS INTEGRATION AND EVOLUTION OFFICE ADVANCED DEVELOPMENT FY 2014 ANNUAL REPORT

## 1. INTRODUCTION

The Advanced Development Group (ADG), part of the Space Launch System (SLS) Program and the Spacecraft/Payload Integration and Evolution (SPIE) Element office, provides the SLS with the advanced development needed to evolve the vehicle from an initial Block 1 payload capability of 70 metric tons (t) to an eventual capability Block 2 of 130 t (fig. 1), with intermediary evolution options possible. ADG takes existing technologies and matures them to the point such that they can be integrated into the mainline program with minimal risk.

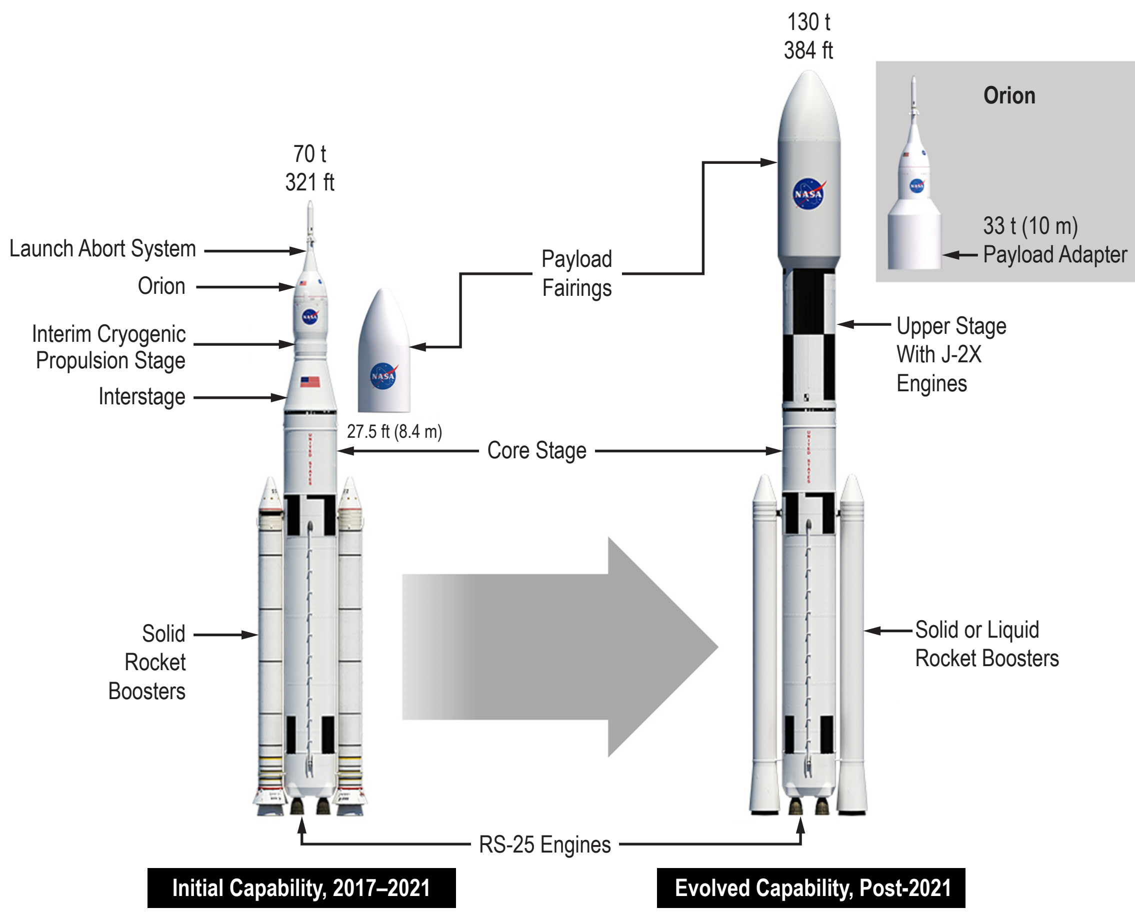



Figure 1. SLS evolvable capability.

The technology maturation path is referred to as the 'Valley of Death.' The Valley of Death is where 'push' technologies normally die due to lack of sponsorship (fig. 2). The adoption of the technology by a program transforms it from a push to a 'pull' technology and helps it to traverse the Valley of Death. Usually, during this period, the funding transitions from the Technology office to the Program office.

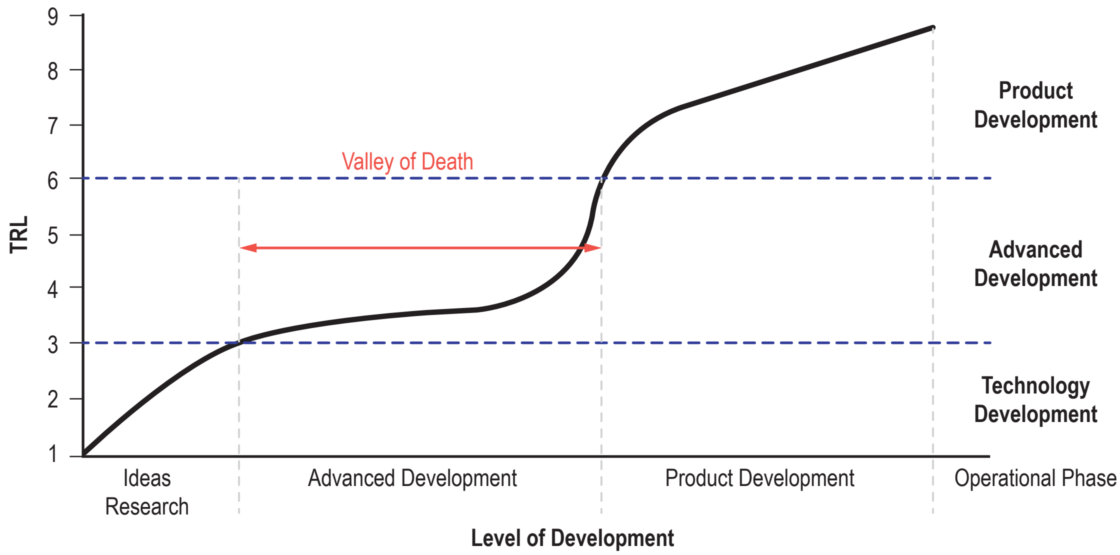



Figure 2. Technology transition.

In order to understand whether or not advanced development is required, it is necessary to systematically assess the maturity of each system, subsystem, or component in terms of the architecture and operational environment. Advanced development defined in the broadest sense can range from a laboratory experiment to the normal development process experienced in a program such as the SLS.

The term 'technology,' as used by NASA, is a reference to hardware maturity. The term Technology Readiness Level (TRL) is used by NASA to measure the maturity of the hardware in relation to where it should be in a normal program lifecycle. Based on the definitions of TRL, the hardware maturity could range from basic principles to the hardware being used in an operational system. Normally, the Valley of Death is considered TRL 3 through 6. The notional flow of ADG transitioning advanced development activities to the SLS hardware elements is shown in figure 3.

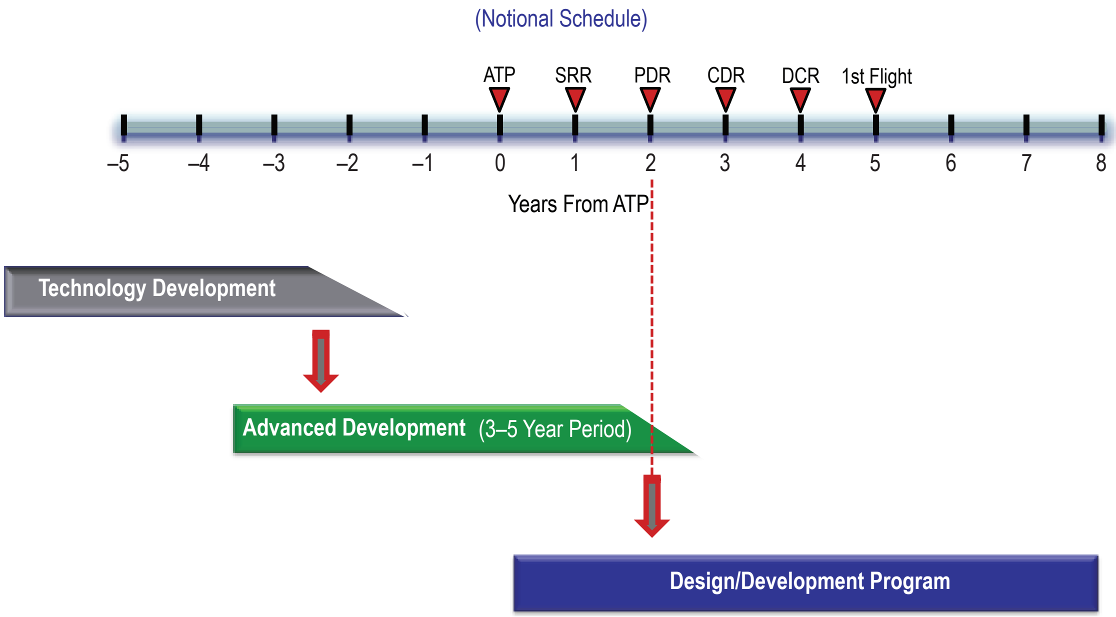



Figure 3. Technology transition to Development program.

The task selection process used by ADG depends upon whether the tasks are conducted in-house or contracted. The selection process for the in-house tasks is discussed in section 2. The contracted tasks are selected by issuing either a NASA Research Announcement (NRA) or a Broad Area Announcement and then competitively selecting and awarding tasks.

### 1.1 Background

The Advanced Development office (ADO) was chartered at the initiation of the SLS program in September 2011. The main tenants of ADO's charter are outlined below:

- Manage the advanced development and Block upgrades required to evolve the launch vehicle to a 130-t lift capability. ADO will work with the SLS program manager (PM) and stakeholders to define the requirements for future Block upgrades.

- Work with the NASA Marshall Space Flight Center (MSFC) Engineering Directorate (ED) and the SLS Element offices to define the Block upgrade configurations.

- Work with ED to mature the configurations and define the resources and schedules for the Block upgrades.

- Prioritize the development and Block upgrade challenges which enable the launch vehicle to evolve to a 130-t lift capability. Advanced development may include grants, in-house and inter-Center activities, and government/industry hybrid model projects.

Based on this charter, ADO issued a call for in-house tasks in February 2012. The in-house tasks were awarded in April 2012. In early fiscal year (FY) 2012, NRAs were issued soliciting industry and academia responses to the Advanced Boosters Engineering Demonstration/Development and Risk Reduction (ABEDRR) and SLS Advanced Development. As a result of the NRAs, tasks were awarded.

In FY 2014, ADG continued the existing academia efforts and awarded two new tasks. The industry and ABEDRR tasks were continued. The initial in-house tasks were reviewed and a call was issued in May 2013 to solicit new tasks focused on an exploration upper stage (EUS) and advanced manufacturing techniques. Many of the initial tasks were extended into FY 2013 and FY 2014. The new in-house tasks were awarded in October 2013. The details of all the tasks are discussed in section 2; a brief summary is provided in figure 4.

**In-house Tasks:**

- Cryogenic Mat'l & Process Development–Mitigate Obsolescence
- Hexavalent Chromium Free Primer for Cryo
- MPS Low Profile Diffuser
- Solide State Ultracapacitor to Replace Batteries Lattice
- Boltzmann Modeling Zero-G Propellants
- Hot fire Test LOX/H2 Additively Manu'f Injector Affordable for EUS
- Testing of Additively Manu'f Turbomachinery
- Additive Manufacturing Infrared Inspection
- Performance Improvement of Friction Stir Welds by Better Surface Finish
- Composite Dry Structure Cost Improvment Approach
- Q2 Inconel 625 Mar'l Properties Development
- Q4 titanium 6–4 Mat'l Properties Development
- Pyroshock Characterization of Composite Materials (NESC funded)
- Booster Interference Loads (NESC funded
- Advanced Booster comp. Case/PBI NBR Insulation Dev (NESC funded)
- Advanced Booster Combustion Stability (NESC funded)

**Academia Tasks:**

- Auburn University: High Electrical Density Device Survey for Aerospace Applications
- Louisiana State University: Improved Friction Stir Welds Using On-Line Sensing of Weld Quality
- Massachusetts Institute of Technology: Modeling Approach for Rotating Cavitation Instabilities in Rocket Engine Turbopumps
- Mississippi State University: Algorithmic Enhancement for High Resolution Hybrid RANS-LES and Large-Scale Multicore Architectures
- University of Florida: Development of Subcritical Atomization Models for Liquid Rocket Injectors and Two-Phase Flow Heat Transfer
- University of Maryland: Validation of Supersonic Film Cooling Numerical Simulations Using Detailed Measurement and Novel Diagnostics
- University of Michigan: Advanced LES and Laser Diagnostics to Model Transient Combustion-Dynamic Processes in Rocket Engines: Prediction of Flame Stabilization and Combustion Instabilities
- Flame Stabilization and Combustion Instabilities University of Utah: Acoustic Emission Based Health Monitoring of Structures
- Pennsylvania State University: Characterization of Aluminum/ Alumina/Carbon Interactions under Simulated Rocket Motor Conditions

**Awarded Industry Tasks:**

- Aerojet: AUSEP Engine Study
- Exquadrum, Inc: AUSEP/DESLA Concept Development
- Moog: AUSE High Press LOX Flow Control Valve Manufacturing Study
- Northrup Grumman: System Requirements and Affordability Assessment for an AUSE
- Pratt & Whitney Rocketdyne: Requirements, Logistics, and System Assessment of an AUSE
- ULA: Integrated Vehicle Fluids (IVF) Testing

**Advanced Booster Engineering Demonstration and Risk Reduction Tasks (ABEDRR):**

- Dynetics & Aerojet: Modernization of the F-1B Engines, Combustion Stability, and Cryotank Manufacturing
- ATK: Demonstration of a FWC for High-Energy Propellant SRB
- Northrop Grumman: Demonstration of a Common Bulkhead LOX/RP Composite Cryogenic Tank

Figure 4. ADG Advanced Development tasks.

## 1.2 Advanced Development Group Organization

### 1.2.1 Organizational Chart

In FY 2014, two Element offices under the SLS program were combined into a single office. The combined offices were the Spacecraft and Integration office and the Advanced Development office. The new office is called the SPIE (shown in fig. 5). The work discussed in this Technical Memorandum is the responsibility of the ADG part of the organization. The contact list for specific tasks is provided in the appendix.

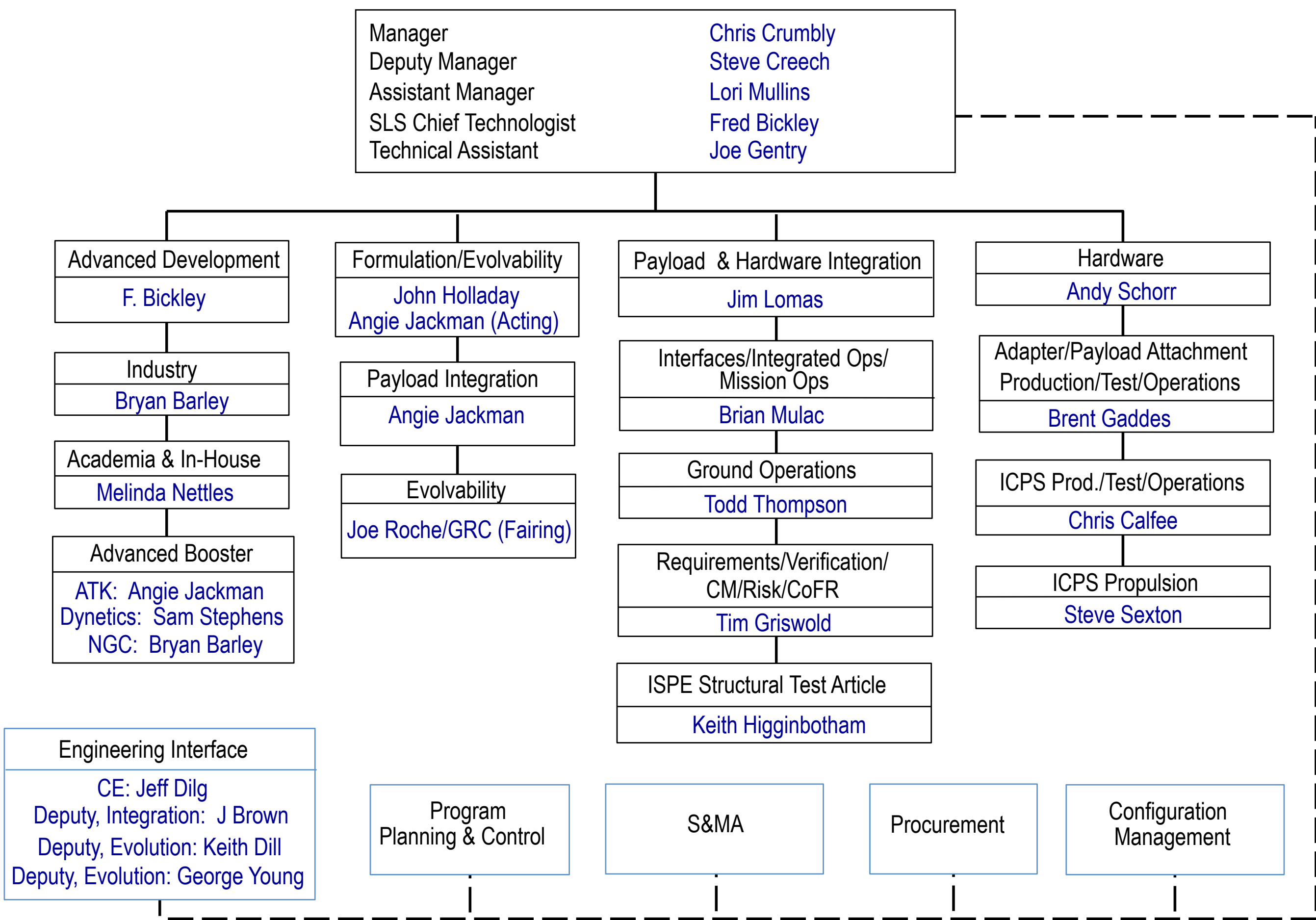



Figure 5. SPIE (XP50) organization.

### 1.2.2 Partnership

ADG has partnered with several organizations, both internal and external, in support of Advanced Development activities. The supporting partners are as follows:

- NASA
  - NASA Engineering and Safety Center (NESC)
  - National Institute for Rocket Propulsion Systems
  - MSFC ED
  - MSFC Safety and Mission Assurance (S&MA) Directorate
  - Other NASA Centers.

- Department of Defense (DoD)
  - U.S. Air Force (USAF)
  - U.S. Army—Aviation and Missile Research Development and Engineering Center (AMRDEC).

Without both the NESC's and the USAF's major investments in the ADG effort, the breadth of ADG's portfolio would have been limited. Their investments have been both financial and through personnel supporting the overall effort.

## 1.3 Funded Tasks

In FY 2014, ADG funded the following number of tasks:

- In-house tasks: 16 (includes the four tasks funded and managed by NESC)
- Academia tasks: 11 (Mississippi State University and the University of Florida each have two tasks)
- Industry tasks: 6
- ABEDRR tasks: 3.

## 1.4 Tasks' Reference Index

For the purpose of easily finding the area of interest, all the tasks have been cross-referenced for applicability to SLS elements and engineering disciplines. The applicability for all tasks is shown in table 1.

## Table 1. Tasks cross-reference matrix.

| Category | Responsible Organization | Proposed Advanced Development Task | Applicability | | | | | | Discipline | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Solid Boosters | Liquid Boosters | Core Stage | Engines | EUS | Shroud | Struc-tures | Thermal | Propulsion | Avionics | Manu-factur-ing |
| MSFC In-House Tasks | MSFC | Cryoinsulation Materials and Process | | | | | | | | | | | |
| | MSFC | Hexavalent Chromium-Free Primer for Cryo | | | | | | | | | | | |
| | MSFC | MPS Low-Profile Diffuser | | | | | | | | | | | |
| | MSFC | A Solid State Ultracapacitor | | | | | | | | | | | |
| | MSFC | Lattice Boltzmann Method for Zero-G Propellant Dynamics | | | | | | | | | | | |
| | MSFC | Hot-Fire Tests LOX/ $H_2$ SLM Injector | | | | | | | | | | | |
| | MSFC | Testing of SLM Turbomachinery | | | | | | | | | | | |
| | MSFC | SLM Infrared Inspection | | | | | | | | | | | |
| | MSFC | Performance Improvement of FSW by Better Surface Finish | | | | | | | | | | | |
| | MSFC | Composite Dry Structure Cost Improvement Approach | | | | | | | | | | | |
| | MSFC | Q2 Inconel 625 Material Properties Development | | | | | | | | | | | |
| | MSFC | Q4 Titanium Material Properties Development | | | | | | | | | | | |
| NASA Tasks | NESC | Pyroshock Characterization of Composite | | | | | | | | | | | |
| | NESC | Booster Interference Loads | | | | | | | | | | | |
| | NESC | Advanced Booster Composite | | | | | | | | | | | |
| | NESC | Advanced Booster Combustion | | | | | | | | | | | |

Table 1.  Tasks cross-reference matrix (Continued).

| Category | Responsible Organization | Proposed Advanced Development Task | Applicability | | | | | | Discipline | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Solid Boosters | Liquid Boosters | Core Stage | Engines | EUS | Shroud | Structures | Thermal | Propulsion | Avionics | Manufacturing |
| Academia | Auburn University | Power Storage Devices | | | | | ■ | | | | | ■ | |
| | Louisiana State College | Improved FSW Using Online Sensing | | | ■ | | ■ | | | | | | ■ |
| | Massachusetts Institute of Technology | Modelling of Cavitation Instabilities | | | | ■ | | | | | ■ | | |
| | Mississippi State University | High Order Unstructured CFD and Large Scale Architectures | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| | Pennsylvania State University | Characterization of Al/Alumina/Carbon | ■ | | | | | | | | ■ | | ■ |
| | University of Florida | Subcritical Atomization Models and Two-Phase Flow Heat Transfer | | ■ | ■ | ■ | ■ | | | ■ | ■ | | |
| | University of Maryland | Supersonic Film Cooling | | | | ■ | | | | ■ | ■ | | |
| | University of Michigan | LES/Laser Diagnostics to Model Transient | | | | ■ | | | | | ■ | | |
| | University of Utah | Acoustic Emission HM of Structures | | | ■ | | ■ | ■ | ■ | | | | |
| Industry | Aerojet | AUSEP Engine Study | | | | ■ | ■ | | | | ■ | | |
| | Exquadrum, Inc. | AUSE/DESLA Concept Development | | | | ■ | ■ | | | | ■ | | |
| | Moog, Inc. | AUSE High-Pressure LOX Flow Control Valve Study | | | | ■ | ■ | | | | ■ | | |
| | Northrup Grumman Systems | AUSE System Requirements and Affordability Assess | | | | ■ | ■ | | | | ■ | | |
| | Pratt & Whitney, Rocketdyne | AUSE Requirements, Logistics and System Assessment | | | | ■ | ■ | | | | ■ | | |
| | United Launch Alllance | Integrated Vehicle Fluids | | | | ■ | ■ | | | ■ | ■ | ■ | |
| ABEDRR | Dynetics & Aerojet | F-1 Engine, Tank Structure, and LOX/RP Combustion Stability | | ■ | | ■ | | | ■ | | ■ | | ■ |
| | ATK | FWC High-Energy Propellant Nozzle | ■ | | | ■ | | | ■ | | ■ | ■ | ■ |
| | Northrup Grumman Systems | Common Bulkhead LOX/RP Composite Tank | | ■ | | | | | ■ | | | | ■ |

## 1.5 Future Plans

The plans for FY 2015 are as follows:

- The first option of the academia efforts that began in FY 2014 will be completed by mid-year. The second year option will be exercised for the approved tasks.

- For both the in-house and industry tasks, new solicitations will be issued mid-year. The tasks are to be awarded by the end of FY 2015.

## 1.6 Summary

The ADG portfolio of tasks covers a broad range of technical developmental activities supporting the evolution of the SLS launch vehicle from the initial 70-t Block 1 vehicle to the 130-t Block 2 vehicle. The ADG portfolio supports the development of advanced boosters, upper stages, and other advanced development activities benefiting the SLS program. The tasks are structured to provide off-ramps on a yearly basis in the event of budget constraints or lack of progress. A summary of the investment made in FY 2014 is shown in table 2. A summary schedule of tasks is shown in figure 6. The task details are discussed in section 2.

Table 2. ADG FY 2014 investment summary.

| Task | FY 2014 Investment ($M)* |
|---|---|
| In-house | 2.4 |
| Academia | 2.4 |
| Industry | 2.3 |
| ABEDRR | 22.0 |

*Substantial resources provided by NESC and the USAF.

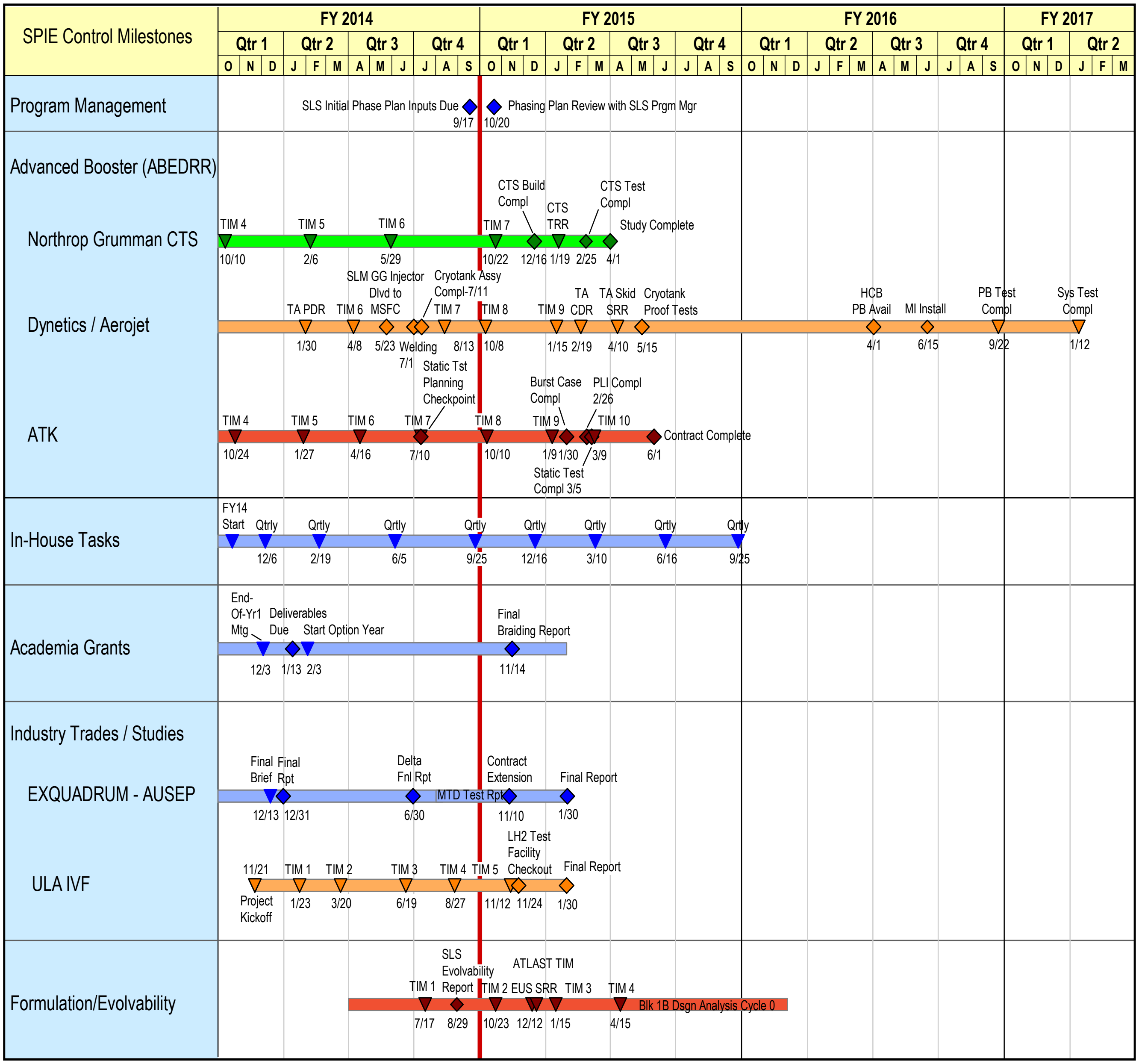



Figure 6. ADG summary schedule.

## 2. TASK DESCRIPTION

This section covers in-house tasks, academia contracts/grants, ABEDRR contracts, and industry contracts.

### 2.1 In-House Tasks

The ADO in-house tasks that are being funded in FY 2014 are listed below (secs. 2.1.2.1 through 2.1.2.12.:

(1) Cryogenic Insulation Materials and Process Development—Mitigate Obsolescence.
(2) Hexavalent Chromium-Free Primer for Cryogenic Application.
(3) Main Propulsion System (MPS) Low-Profile Diffuser.
(4) Solid-State Ultracapacitor to Replace Batteries.
(5) Lattice Boltzmann Method for Modeling Cryogenic Stage Zero-G Propellant Dynamics.
(6) Hot-Fire Test of $LOX/H_2$ SLM Injector Applicable to EUS.
(7) Testing of Selective Laser Melting (SLM) Turbomachinery Applicable to EUS.
(8) Additive Manufacturing (AM) Infrared Inspection.
(9) Performance Improvement of Friction Stir Welds (FSWs) by Better Surface Finish.
(10) Composite Dry Structure Cost Improvement Approach.
(11) Q2 Inconel 625 Material Properties Development.
(12) Q4 Titanium 6-4 Material Properties Development.

The NESC selected to fund and manage the following four additional tasks not funded by the ADO (secs. 2.1.3.1 through 2.1.3.4):

(1) Pyroshock Characterization of Composite Materials.
(2) Booster Interference Loads.
(3) Advanced Booster Composite Case/Polybenzimidazole-Nitrile Butadiene Rubber (PBI-NBR) Insulation Development.
(4) Advanced Booster Combustion Stability.

#### 2.1.1 Selection Methodology

The selection process used for the in-house tasks is shown in figure 7. ADG releases a call for proposals to MSFC ED with encouragement to solicit inputs from other NASA Centers. The call specified that the proposed tasks must be consistent with reasonably expected technical advances and realistic budgetary constraints, and must address one or more of the following figures of merit (FOMs):

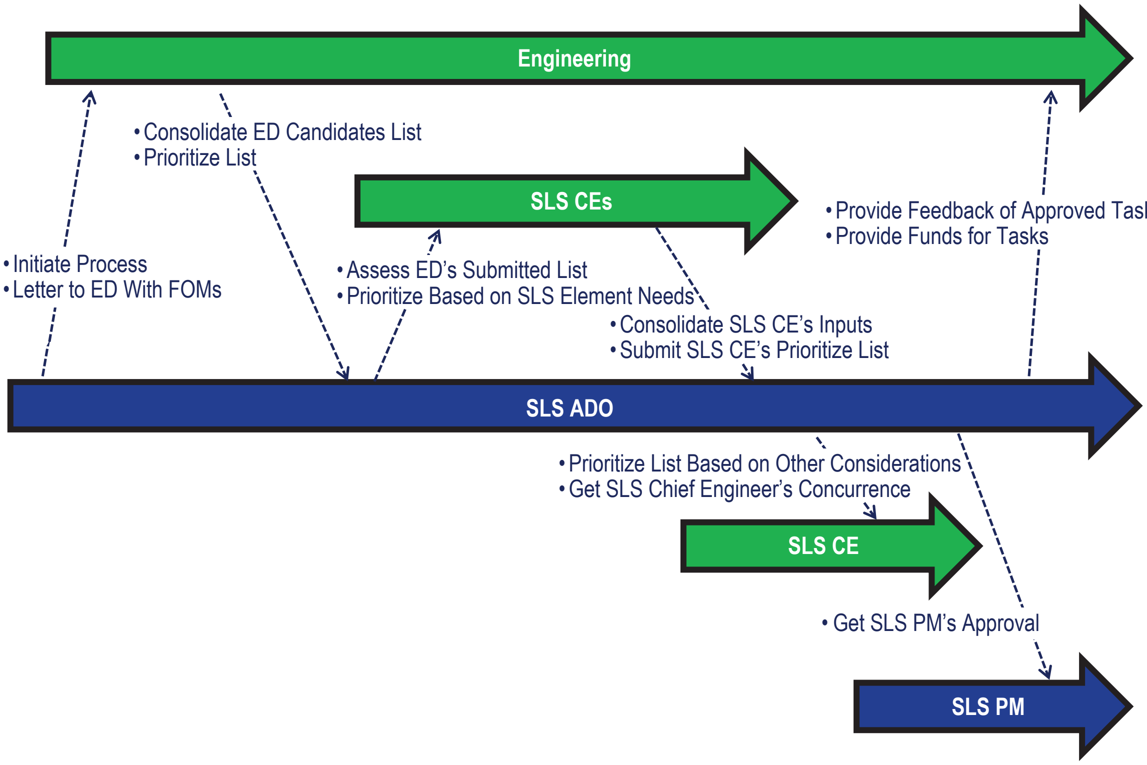



Figure 7. In-house task selection process.

- Improvements in affordability.
- Improvements in safety.
- Improvements in reliability.
- Improvements in performance.

Generally, the ED develops proposals and solicites inputs from other Centers. The proposals are in the form of quad charts. Departments within ED review and rank the proposals. A panel of ED senior managers convenes to review and prioritize the proposed tasks. After this is completed, the results are presented to ADG. The SPIE chief engineer (CE) then convenes a panel consisting of all the SLS CEs and the SLS chief safety officer (CSO) to review the proposed tasks and assess their applicability and priority to both the current Block 1 SLS vehicle and the evolved vehicle concepts. They provided their assessment to ADG by categorizing the tasks in high, medium, and low priorities.

Based on the CE and CSO inputs, ADG selects a set of high-priority tasks that would fit within the allocated resources available. This final list is then vetted through the SLS CE and presented to the SLS SPIE manager for final approval. ADG then gives ED the authority to proceed (ATP) at an in-house tasks kickoff meeting.

### 2.1.2 Advanced Development Group-Funded Task Descriptions/Status

#### 2.1.2.1 Cryogenic Insulation Materials and Process Development—Mitigate Obsolescence.

2.1.2.1.1 Description. Current cryogenic insulation materials, originally developed for the Constellation program and later transitioned to the SLS program, are classified as ozone-depleting substance, environmentally compliant materials. The SLS core stage cryoinsulation foams are formulated with the blowing agent HFC-245fa, a Global Warming Potential (GWP) material. While the Environmental Protection Agency has not begun to regulate GWP materials, it has levied a usage reporting requirement, which historically is the first step towards regulation. They are on the watch list and are proposed for eventual phase-out.

It is expected that the foam industry will be testing new materials in small quantities and will likely transition them into production to avoid obsolescence-related shortages. These industry applications are different from aerospace applications, so the new foam systems will require aerospace-specific development and testing similar to that performed by MSFC for current cryogenic insulation systems.

This task will investigate low GWP cryoinsulation foams as a proactive risk mitigation for the SLS Core Stage. Specifically, the task will perform a market survey and begin bench scale lab testing of low GWP cryoinsulation foams.

2.1.2.1.2 Accomplishments. The market survey for low GWP cryoinsulation foams has been completed, with the findings as follows:

- Primary aerospace foam vendors and large chemical companies in the blowing agent industry are focused on hydrofluoroolefin (HFO) molecule blowing agents:
  - HFO blowing agents are not yet stable in foam formulations.
  - Foams formulation with HFOs have a short shelf life and do not pass burn tests.
  - Low GWP foams with HFO blowing agents were not available for bench scale lab testing in FY 2014.

- Smaller foam vendors have alternative low GWP blowing agent possibilities:
  - Pentane is a flammable blowing agent. Although the capability exists to use this agent in MSFC's foam spray booth, the manufacturing locations at the Michoud Assembly Facility (MAF) do not have class 1, division 1 facilities for foam spray so implementation would not likely be realized. This will not be pursued at this time but remains a possibility.
  - Using a water/carbon dioxide ($CO_2$) combination as a blowing agent will provide a closed cell foam of acceptable density but may not insulate as well. This is worth investigating to test the insulative capability. Icynene, manufacturer of water/$CO_2$-blown ProSeal Eco, is willing to apply the foam to our aluminum substrate panels for test purposes. Work is underway to ship panels for the foam application.
  - A new low GWP blowing agent, methyl formate (trade name Ecomate®) is patented by Foam Supplies Incorporated (FSI). In discussions with FSI, they have expressed a desire to formulate a new foam with Ecomate to specifically address our aerospace foam requirements. A list of basic requirements has been provided to FSI.

2.1.2.1.3 Future Work. Obtaining sprayed foam samples from Icynene and performing density and thermal conductivity testing is on the list of future work. Discussions will continue with FSI to formulate a cryoinsulation foam with methyl formate and continue to stay apprised of industry advances in formulating foam with low GWP blowing agents. To date, foam samples for bench scale testing have not been available due to the following issues:

- HFO blowing agent not yet stable in current foam formulations.

- Water/$CO_2$ blown foams are formulated by a Canadian company, complicating shipment of panels to them for spray application.

- Methyl formate blown foams are new to the market and require custom formulation.

**2.1.2.2 Hexavalent Chromium-Free Primer for Cryogenic Application.**

2.1.2.2.1 Description. This task involves identifying a commercially available hexavalent, chromium-free primer for cryogenic applications. The need for a new primer is driven by the carcinogenic nature of, the manufacturing cost associated with, and the high potential for obsolescence of currently qualified primers that contain hexavalent chromium.

Hexavalent chromium-based primers are applied to metallic cryogenic tank structures to provide corrosion protection and promote adhesion for thermal protection system materials. Hexavalent chromium is considered a hazardous material and its availability for future programs is questionable, since its customer base is switching to nonhazardous alternatives. The primary user, the DoD, does not, in general, require cryogenic performance, so alternative materials have been made more readily available for their applications.

This effort evaluates the corrosion protection capability of several hexavalent chromium-free primers under simulated launch vehicle-related conditions (fig. 8). Results will provide sufficient data to either recommend these materials for qualification testing or remove them from consideration. Applications include replacement of current hexavalent chromium primers used on the SLS structure beneath thermal protection system materials. The resulting materials will be environmentally friendly and should reduce operations costs associated with hazardous waste usage and disposal.

Figure 8. Hexavalent chromium-free test panels.

2.1.2.2.2 Accomplishments. Based on the preliminary testing (phase 1) conducted in 2013, four candidate primers passed into phase 2 testing in 2014. Some of the four candidates have the potential to continue additional screening efforts based on successful physical tests and cryogenic performance and have the potential to replace traditional chromium-based primers. Of the four candidates, Desoprime CF/CA 7502 has the greatest potential to continue development. This primer did exceedingly well in all tests and should be considered for continued future evaluations. Hexavalent chromium-free primer development task personnel will continue to work with industry to identify potential candidates and potential modifications to these candidates to meet NASA/SLS cryogenic requirements.

2.1.2.2.3 Future Work. The use of chromate-based primers is quickly moving toward obsolescence and work should continue on evaluations of new and promising green, anticorrosive primers that are acceptable for use in cryogenic applications.

#### 2.1.2.3 Main Propulsion System Low-Profile Diffuser.

2.1.2.3.1 Description. Pressurization diffusers are used to introduce pressurization gases into a rocket's propellant tanks. This pressurization gas is used to keep the tanks pressurized as the rocket engine burns and drains the propellants. The diffuser's role is to introduce the gases into the tank without significant velocity. Typical diffusers are long and limit the amount of propellants that can be loaded into the tanks. A smaller, more compact diffuser would allow more liquid propellant to be loaded into the tank, which in turn helps increase the rocket's performance.

The purpose of this task is to create a low-profile pressurization diffuser (fig. 9) that is more compact than traditional pressurization diffusers. This task uses computational fluid dynamics (CFD) to design a low-profile diffuser. The flow passing through the diffuser was analyzed to determine how the exiting gases flow into the tank.

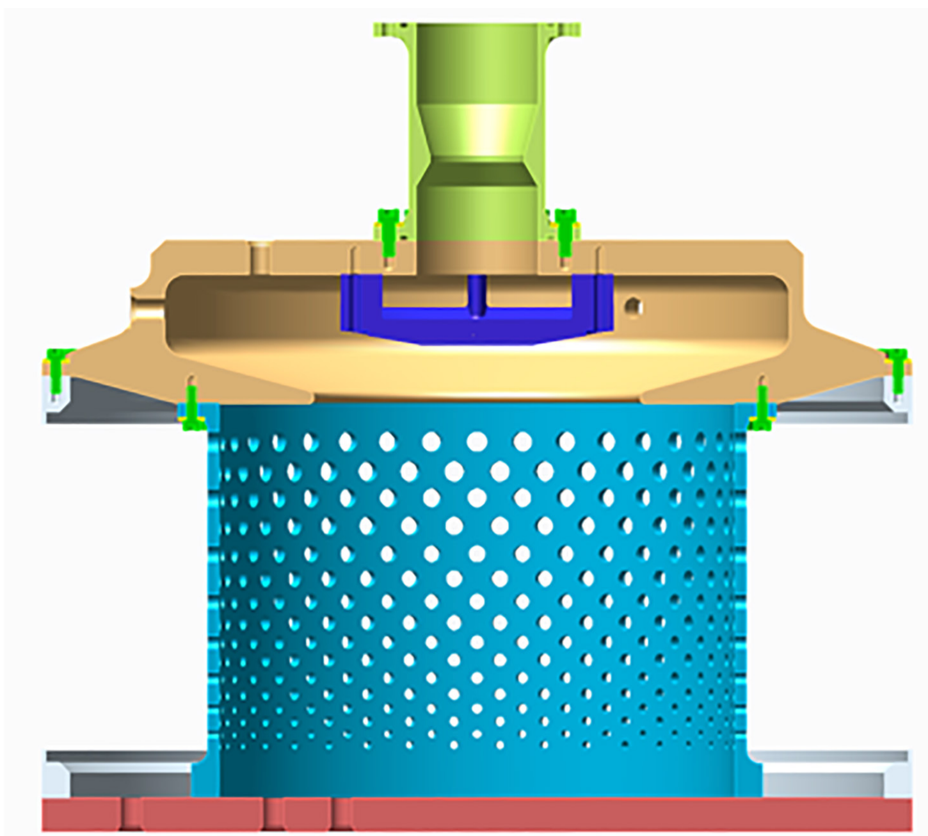
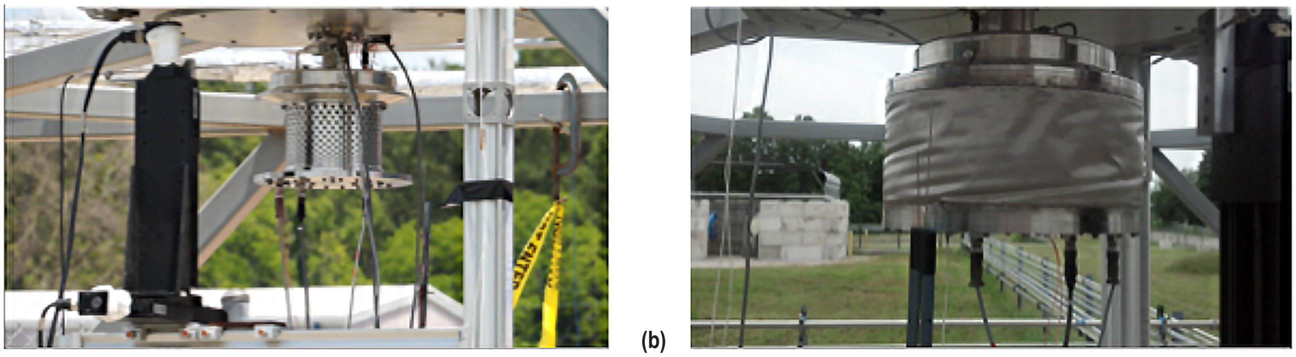


Figure 9. Low-profile diffuser design.

2.1.2.3.2 Accomplishments. The prototype diffuser has completed flow testing to validate CFD models. The results indicate good agreement between CFD and data. Figure 10 shows the two configurations test setup for the diffuser.




(a) (b)

Figure 10. Low-profile diffuser test setup: (a) Without wire cloth and (b) with wire cloth.

2.1.2.3.3 Future Work. Since both the Boeing baseline SLS/Block 1 core diffuser and the low-profile diffuser were tested in the same facility, a direct comparison of the test results for the low-profile diffuser with the test results for the SLS core diffuser will be performed. Once the final test report is written, the ADO support of this activity will be ended.

**2.1.2.4 Solid-State Ultracapacitor to Replace Batteries.**

2.1.2.4.1 Description. This task is for research and development activities leading to a solid-state ultracapacitor to replace batteries. The task is focused on internal barrier layer capacitor structures composed of barium titanate (BT) coated with various materials using atomic layer deposition (ALD) techniques. Hybrid approaches using polymer/ceramic mixes as well as material doping will also be considered. Single-layer ultracapacitor cells will be fabricated and tested. The tasks are divided into the following four separate areas: (1) Evaluate spark plasma sintering at the Oak Ridge National Laboratory (ORNL), (2) evaluate zirconia and titania coatings over BT, (3) evaluate polyimide/BT hybrid ultracap cells, and (4) evaluate single-layer ultracap cells.

2.1.2.4.2 Accomplishments. The accomplishments for FY 2014 are as follows:

- Evaluation of the Spark Plasma Sintering at ORNL task was completed. The team spent a week at ORNL fabricating ultracaps from coated BT powders. These were then tested at MSFC and more thoroughly by Auburn University. The technique shows great promise, as giant permittivity was observed; however, other ultracap properties are not yet desirable, so more experimentation in the future will be conducted. A spinoff benefit from this research is that the NASA Nuclear Fuel team leveraged the ORNL funding to conduct initial experiments on surrogate nuclear fuel material and had excellent results. This process is being pursued so that MSFC may get the capability in-house, which will expedite future densification studies and nuclear propulsion.

- A complete evaluation of zirconia as an alternate coating was conducted. The findings from MSFC and Auburn University show an inconsistent coating from the current coating vendor. To get around this issue, a new ALD vendor at North Carolina State University (VaporPulse) has been contracted so that their process can be evaluated.

- A substantial amount of research in evaluating composite polyimide/BT dielectric materials has been carried out. This research has also included the development of new 3D printing processes and materials. Another spinoff research benefit is that a new, unique low-temperature silver (Ag) electrode ink has been developed that has great potential not only for ultracapacitors, but for all 3D circuit printing in the future (fig. 11). This new ink is expected to solve the problem of coating diffusion into the core. Ultracap samples with ALD-coated BT in solution with the polyimide have been constructed and have undergone initial testing with promising results.

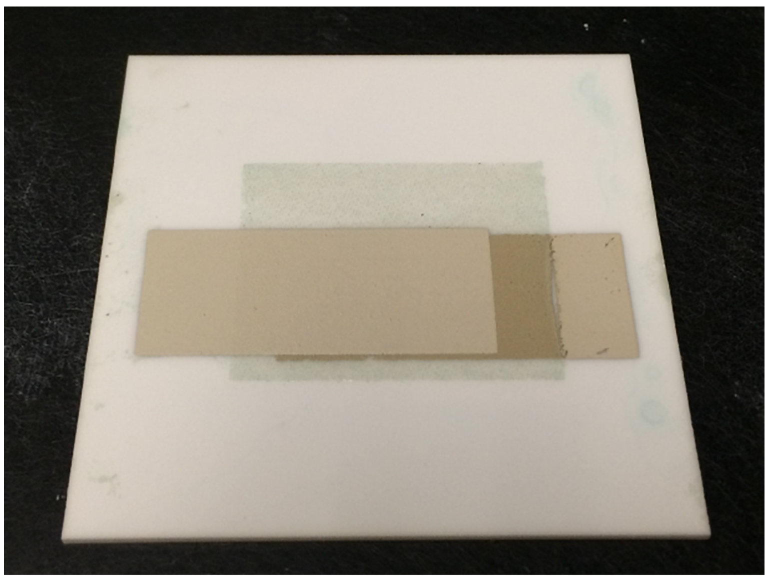


Figure 11. Composite ultracap with new Ag ink.

- Evaluation of many variations of the single-layer ultracap cell have been completed with dielectric inks formulated from the various ALD-coated BT and doped perovskite ceramic materials; see figure 12. Some of these have shown excellent ultracap properties. A number of new processes to optimize the processing and development of materials for ultracaps have also been developed this year, including 3D and additive printing, new low temperature curing, and submicron powder milling with vibratory mill.

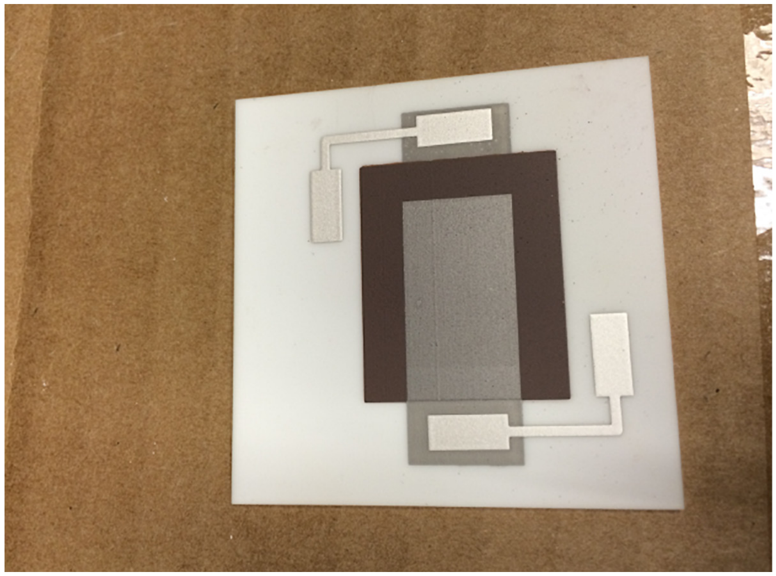


Figure 12. Ultracap device from doped-BT material.

2.1.2.4.3 Future Work. Titania ALD coatings will be evaluated. Ultracap samples with more dielectric formulations are being developed for further evaluation. Evaluation of many variations of the single-layer ultracap cell have been completed with dielectric inks formulated from the various ALD-coated BT and doped perovskite ceramic materials. Variations of the single-layer ultracap cells with dielectric inks formulated from the various ALD-coated BT and doped-perovskite ceramic materials.

**2.1.2.5 Lattice Boltzmann Method for Modeling Cryogenic Stage Zero-G Propellant Dynamics.**

2.1.2.5.1 Description. This task involves developing a new capability to predict liquid propellant sloshing/bulk motion effects on the spacecraft vehicle dynamics in low-g environments associated with flight conditions such as loiter, startup/shutdown transients, and during maneuvering. Accurate modeling of the coupled dynamic behavior of liquid propellants in the low-g environment is crucial to mitigating risks such as undesirable liquid venting and interaction with the spacecraft attitude control system. Nonlinear effects due to a changing acceleration field perturb the integrated spacecraft-liquid dynamics and must be evaluated in flight mechanics simulations. The Lattice Boltzmann Method (LBM) has recently emerged as a promising alternative to traditional CFD techniques due to its high computational efficiency, which may allow liquid models to be integrated with simulations of spacecraft dynamics rather than run offline. Integration of CFD with guidance, navigation, and control (GN&C) flight mechanics simulations would enable an unprecedented capability for preventing adverse fluid-vehicle interaction. A 2D, two-phase LBM flow solver will be developed for a proof-of-concept rapid, parallelizable coupled vehicle-fluid simulation of free surface flows in spacecraft propellant tanks in microgravity and time-varying acceleration fields.

2.1.2.5.2 Accomplishments. The following have been accomplished for this task:

- Investigated suitability of LBM approaches for propellant dynamics modeling in microgravity.

- Developed a modular MATLAB®-based 2D flow solver.

- Determined sensitivities of LBM CFD approach to parameters (grid spacing, boundary conditions, time step, applied acceleration) on stability and error.

- Applied a novel approach to resolving body forces through global momentum conservation.

- Developed an analytic method for mapping real fluid properties into the LBM framework using the Carnahan-Starling equation of state.

- Demonstrated stable, two-phase flow with accurate steady-state density for a subcritical cryogen in a closed domain (LOX @ 94K, $T/Tc = 0.608$).

2.1.2.5.3 Future Work. The following is work remaining for FY 2014 and plans for FY 2015:

- Analysis of single-component test cases.

- Investigation of pressure accuracy and stability issues at low kinematic viscosities and larger accelerations.

- Development of phase I report to document findings.

- Development of work plan for phase II (FY 2015):
  – Implementation of 3D model.
  – Investigate extensions to improve stability.
  – More extensive verification with analytical solutions and test data (if available).

**2.1.2.6 Hot-Fire Test of Liquid Oxygen/Hydrogen Selective Laser Melting Injector Applicable to the Exploration Upper Stage**

2.1.2.6.1 Description. This task is to hot-fire test an existing SLM injector that is applicable for all expander cycle engines being considered for the exploration upper stage. The work leverages investment made in FY 2013 that was used to additively manufacture three injectors (fig. 13), all by different vendors.

Figure 13. Manufactured LOX/$H_2$ SLM injectors.

2.1.2.6.2 Accomplishments. Accomplishments include selecting two of the injectors to use for hot-fire testing and completing the following tasks:

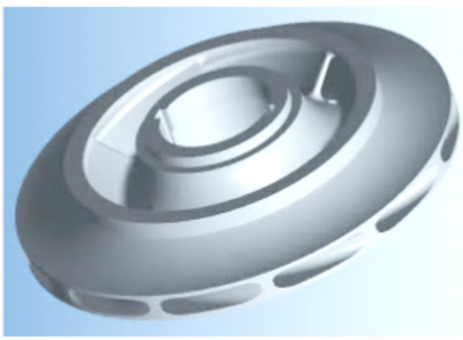
- Performed nondestructive evaluation (NDE) on the original SLM injectors.
- Machined and welded the Rigimesh face plate.
- Water flow tests.
- Fabricated the ablative chambers used to support testing.
- Test facility buildup, wrote the Test Requirements Document and successfully completed the Test Readiness Review (TRR).
- Performed facility leak checks and blowdown tests.
- Hot-fire tests of injectors (fig. 14).

Figure 14. Water flow and hot-fire testing of two LOX/$H_2$ SLM injectors.

2.1.2.6.3  Future Work.  All work associated with this task has been successfully completed. This task can now be leveraged to perform additional development and testing of additively manufactured propulsion hardware including ducts, valves, injector, and turbomachinery hardware.

**2.1.2.7  Testing of Selective Laser Melting Turbomachinery Applicable to the Exploration Upper Stage.**

2.1.2.7.1  Description.  This task is to design, fabricate, and spin test to failure a Ti6-4 hydrogen turbopump impeller that was built using the SLM fabrication process (fig. 15). The impeller is sized around upper stage engine requirements. In addition to the spin burst test, material testing will be performed on coupons that are built with the impeller.



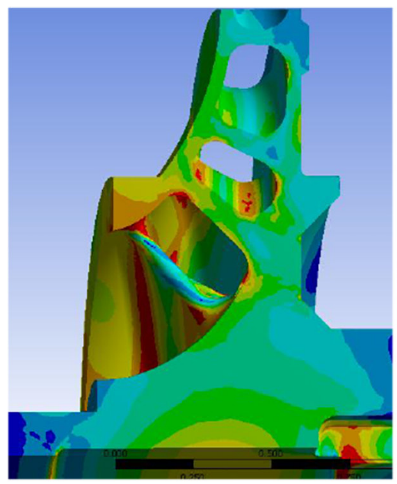


Figure 15.  SLM turbopump impeller design.

2.1.2.7.2  Accomplishments.  Accomplishments for this task include the design of the SLM impeller; impeller and material coupon fabrication; final machining (fig. 16); structured light scanning and inspection, spin burst testing, material strength data development; and data analysis. The spin test was successfully performed and operated up to 147,600 rpm, with the result that the impeller could not be failed with the equipment used.

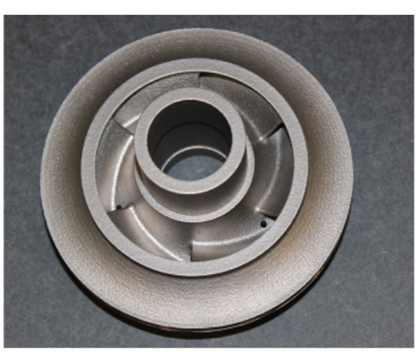


Figure 16.  SLM Ti6-4 manufactured turbopump impeller.

2.1.2.7.3 Future Work. All work associated with this task has been successfully completed. This task can now be leveraged to perform additional development and testing of additively manufactured propulsion hardware including ducts, valves, injector, and turbomachinery hardware, including an integrate liquid hydrogen ($LH_2$) turbopump test.

**2.1.2.8 Additive Manufacturing Infrared Inspection.**

2.1.2.8.1 Description. The AM infrared inspection task started the development of a real-time dimensional inspection technique and digital quality record for the AM process using infrared camera imaging and processing techniques. The AM infrared inspection will benefit AM by providing real-time inspection of internal geometry that is not currently possible. Additive Manufacturing Infrared Inspection will reduce the time and cost of additive manufactured parts with automated real-time dimensional inspections which deletes post-production inspections.

2.1.2.8.2 Accomplishments. The task successfully proved the feasibility of infrared hardware detecting AM process (fig. 17). Custom software was developed to create 3D geometry files of the additive manufactured part (fig. 18).

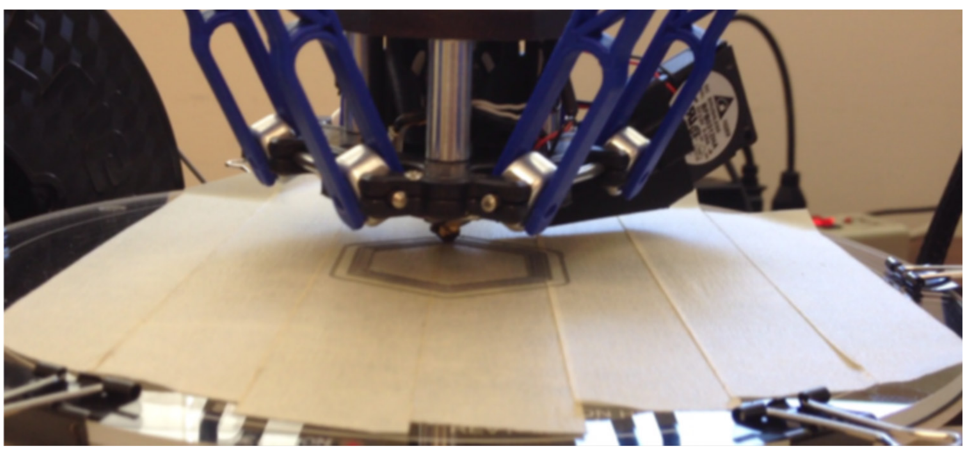


Figure 17. Orion Delta 3D printer and manufactured part.

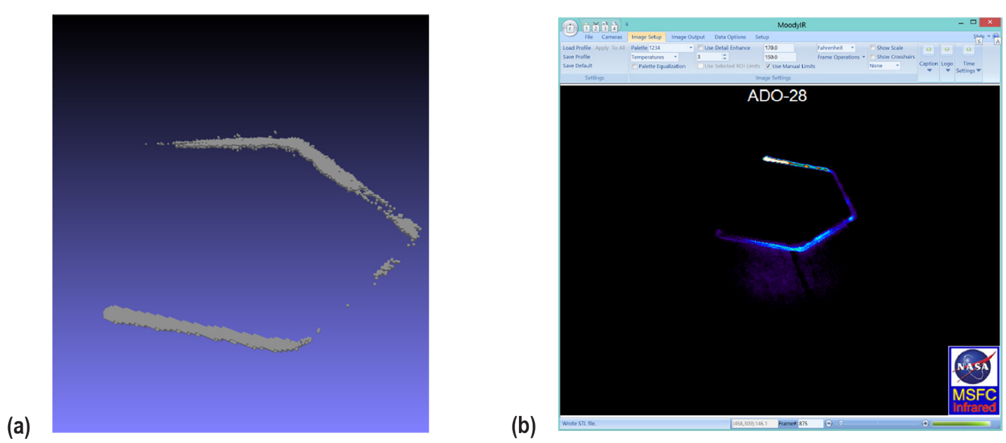



Figure 18. Test results of detecting additive manufactured part: (a) CAD image of printed part and (b) software display of infrared temperature of part.

2.1.2.8.3 Future Work. Continued future work includes the development of real-time dimensional inspection technique and digital quality records using infrared camera imaging and processing techniques.

**2.1.2.9 Performance Improvement of Friction Stir Welds by Better Surface Finish.**

2.1.2.9.1 Description. The as-welded friction stir weld has a cross section that may act as a stress concentrator. The geometry associated with the stress concentration may reduce the weld strength and it makes the weld challenging to inspect with ultrasound. In some cases, the geometry leads to false positive NDE indications and, in many cases, it requires manual blending to facilitate the inspection. This study will measure the stress concentration effect and develop an improved phased array ultrasonic testing (PAUT) technique for FSW.

Post-welding, the FSW tool would be fitted with an end mill that would machine the weld smooth, trimmed shaved. This would eliminate the need for manual weld preparation for ultrasonic inspections. Manual surface preparation is a hand operation that varies widely depending on the person preparing the welds. Shaving is a process that can be automated and tightly controlled.

2.1.2.9.2 Accomplishments. Two sets of panels will be welded with FSWs. One set will be prepared in the usual manner and the second set will be shaved by milling. These panels will be used to estimate the phased array testing detectability of defects in the surface. The defects will be electro-discharge machining (EDM) notches placed in and along the weld. Then, samples will be cut from these panels and pulled in a tensile test machine to measure the strength of the shaved and unshaved panels.

- Baseline self-reacting-friction stir weld (SR-FSW) panels:
  - Eight baseline panels have been welded and PAUT tested.
  - Two baseline panels have been machined into tensile specimens for room temperature, liquid nitrogen ($LN_2$), and $LH_2$ testing; this work is complete.
  - Five baseline panels have been laid out for EDM notches; this work is complete.
  - One EDM notched baseline panel has been given to EM10 to measure the notches; however, they are having trouble measuring the notches. A few workarounds are currently being assessed.
- SR–FSW panels with raised weld-land (≈0.025 inch):
  - One panel with raised weld-land was welded to determine the best method for machining the raised weld-land.
  - Seven panels with raised weld-land have been welded and PAUT inspected; these panels had a slight ridge that was not machined off. The panels were hand-sanded to remove the slight

ridge, then reinspected with PAUT. Five panels were identified for probability of detection (POD) inspections.

– Two panels with raised weld-land have been machined into tensile specimens for room temperature, $LN_2$, and $LH_2$ testing; this work is complete.

– Five panels with raised weld-land have been laid out for EDM notches and the work has been scheduled.

2.1.2.9.3 Future Work. The following work is planned:

• NDE POD on shaved prepared panels (smoothed).

• NDE POD on baseline panels (manual).

• Prepare report with results, lessons learned, and recommendations for FY 2015 work.

**2.1.2.10 Composite Dry Structure Cost Improvement Approach.**

2.1.2.10.1 Description. This effort demonstrates that by focusing only on properties of relevance, composite interstage and shroud structures can be placed on the SLS vehicle that simultaneously reduce cost, improve reliability, and maximize performance, thus providing the SLS with a new methodology of how to utilize composites to reduce weight for composite structures on launch vehicles. Interstage and shroud structures were chosen since both of these structures are simple in configuration and do not experience extreme environments (such as cryogenic or hot gas temperatures) and should represent an appropriate starting point for flying composites on a 'human-rated' vehicle. They are used as an example only.

The task consisted of monthly presentations on the subject matter of using polymer matrix composites for launch vehicle structures given from January 2014 through October 2014. A final summary documenting major points is to be done at the conclusion of this task. Each monthly topic presents the logic and rationale behind the proposed new methodology.

2.1.2.10.2 Accomplishments. The presentations have addressed the following issues that are barriers to using composites and given rationale as to how to remedy them:

• Testing of lamina is not only expensive and difficult but futile since no laminate failure criteria has been shown to be valid for practical use.

• Undamaged laminate testing is time consuming and costly. This is hard to justify as these strength numbers will probably never be used since damage must be assumed to exist in the laminate.

• Undamaged laminate testing is more of a 'test of the test method' rather than a material property test.

- If a structure has a dominant loading case, such as compression for an interstage structure, then characterizing other strength, such as tension, is of no practical use.

- Costly fatigue testing is usually not necessary.

- The statistical significance (the obtaining of which is very costly) of the multitude of undamaged test specimens is lost many times over by the time a final design number for a given piece of hardware is agreed upon.

- The final product will have an optimum layup based on undamaged properties that may not result in an optimum layup for damage tolerance considerations. This may contribute to design values that are either too high (poor reliability) or too low (compromised performance) being used.

2.1.2.10.3 Future Work. No future work is planned.

**2.1.2.11 Q2 Inconel 625 Material Properties Development.**

2.1.2.11.1 Description. This task involves development and characterization of SLM parameters for AM of nickel alloy 625 (aka Inconel 625 or In625). SLM is a relatively new manufacturing technology that fabricates complex metal components by fusing thin layers of powder with a high-powered laser beam, utilizing a 3D computer design to direct the energy and form the shape without traditional tools, dies, or molds. There are several metal SLM technologies and materials on the market today, and various efforts to quantify the mechanical properties, however, nothing consolidated or formal to date. Meanwhile, SLM material strength properties of In625 are currently highly sought after by NASA propulsion designers for liquid rocket engine components.

The primary objective of this task is to utilize MSFC's existing SLM equipment and knowledge base with other metal alloys to generate a reduced design allowables database of expected properties for SLM In625 parts. This first requires a series of experiments (fig. 19) aimed at optimizing build parameters in the SLM machine to build parts that demonstrate peak properties based on a global energy input probability test matrix. Once a base set of operating parameters is determined, the team will build and test the required number of mechanical coupons to serve as a basis for follow-on allowables development.

(a) (b)

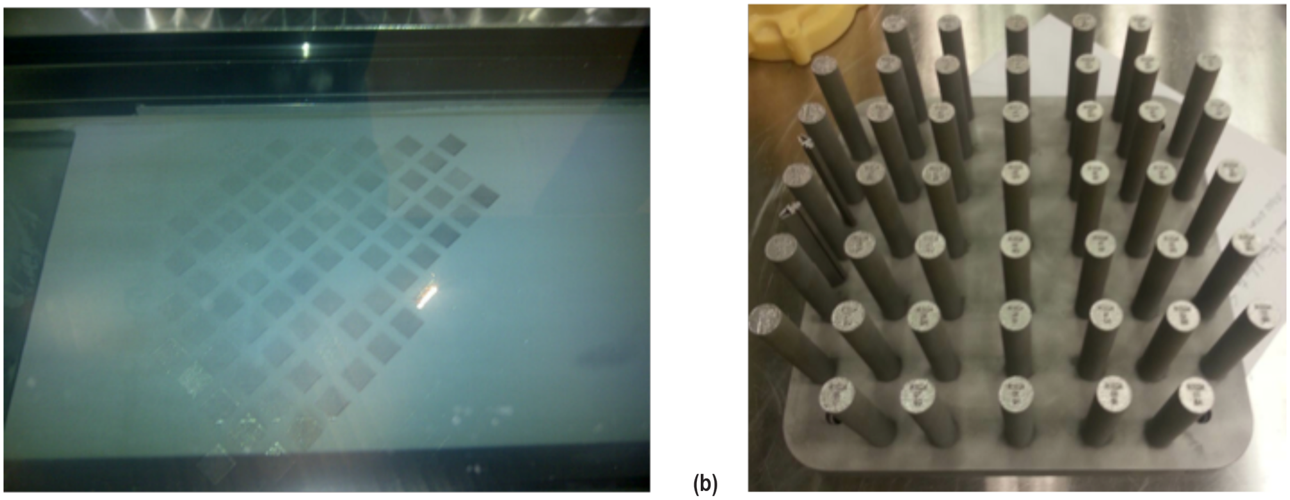


Figure 19. Inconel 625 samples: (a) Samples being built and (b) completed samples ready for testing.

2.1.2.11.2 Accomplishments. The following tasks were completed:

- Design of experiments on 100 samples to determine the effects of changes in the global energy input on Rockwell hardness of produced coupons.

- Those test data were then used to build a sample set of 50 coupons to test the resulting tensile strength at room temperature in hopes of selecting one set of parameters to run a larger, 184 coupon sample set of tensile, fracture, and fatigue coupons.

- The data actually show a large range of acceptable parameters (fig. 20).

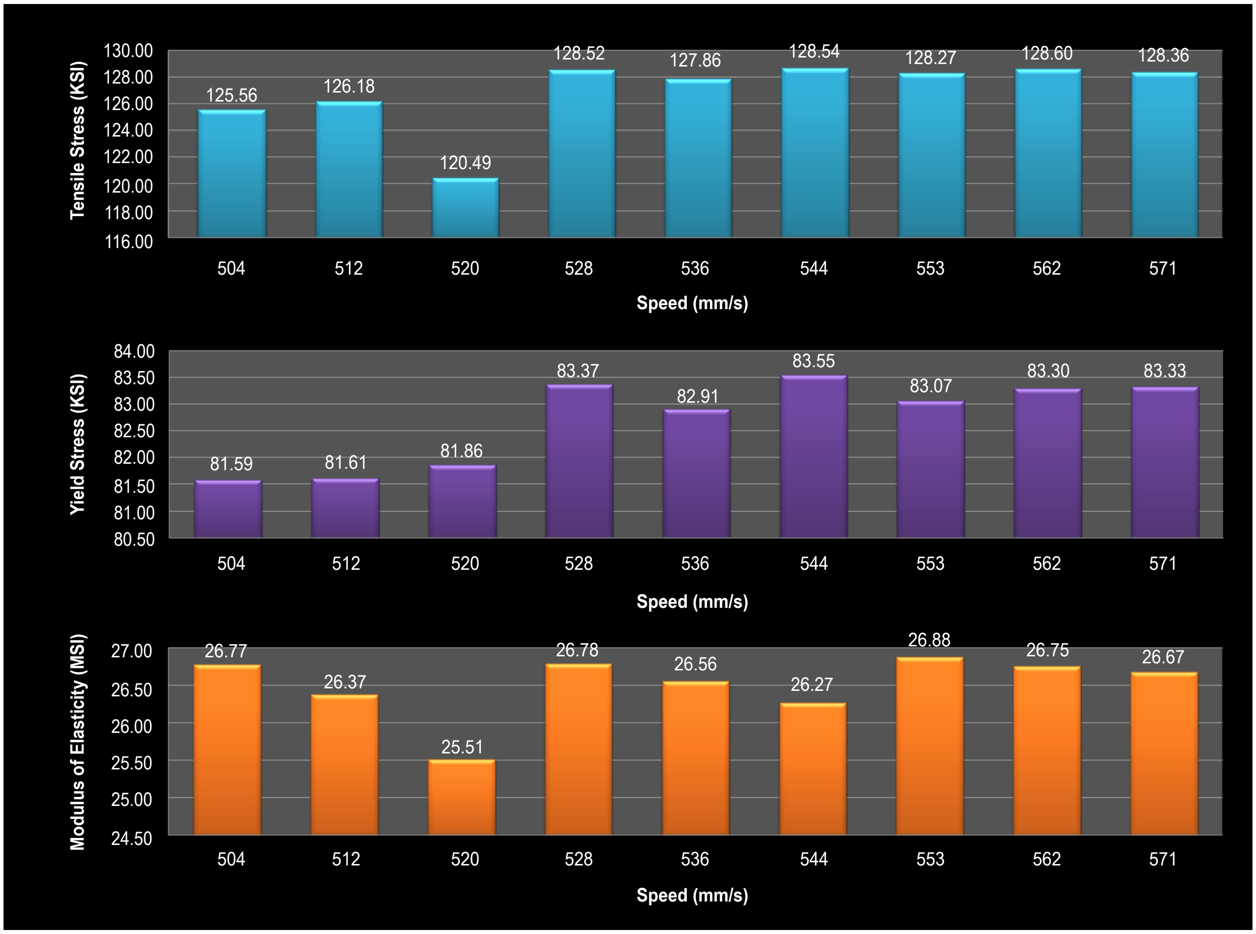



Figure 20. Inconel 625 samples test results.

2.1.2.11.3 Future Work. The team is assessing the most beneficial test path forward. Most likely, the next set of tests will use the fastest acceptable parameters and focus more on the various heat treatments required after the SLM build to boost the mechanical properties.

**2.1.2.12 Q4 Titanium 6-4 Material Properties Development.**

2.1.2.12.1 Description. This task involves development and characterization of SLM parameters for AM of titanium-6%aluminum-4%vanadium (aka Ti-6Al-4V or Ti64). SLM is a relatively new manufacturing technology that fabricates complex metal components by fusing thin layers of powder with a high-powered laser beam, utilizing a 3D computer design to direct the energy and form the shape without traditional tools, dies, or molds. There are several metal SLM technologies and materials on the market today, and various efforts to quantify the mechanical properties, however, nothing consolidated or formal to date. Meanwhile, SLM material fatigue properties of Ti64 are currently highly sought after by NASA propulsion designers for rotating turbomachinery components.

The primary objective of this task is to generate a reduced design allowables database of expected properties for SLM Ti64 parts and utilize MSFC's existing SLM equipment (fig. 21) and knowledge base with other metal alloys. Unlike Inconel 625, Ti64 has never been used in MSFC's ConceptLaser SLM machine prior to this development effort. Therefore, the initial build development is done first, followed by parameter optimization. Initial build development entails finding the correct general parameters, build plate materials, and build settings that yield satisfactorily dense (>99.5%) parts that will build to completion. Initial build development also entails maintaining and further honing our safety protocols around Ti-6Al-4V. As a reactive powder, it requires vigilant grounding and safety consciousness in order to expose the minimal number of operators to the least risk for the smallest amount of time.

Figure 21. SLM machine with glovebox required for Ti6-4.

2.1.2.12.2 Accomplishments. The first build plate was a set of four small material test samples built on a stainless steel 90-mm × 90-mm build plate. Four samples were run at 250 W, 1,600 mm/s with varying spot sizes in an effort to quantify the melt pool size of Ti-6 Al-4V in the SLM. Part parameters were based on parameters successfully used at KU Leuven on a similar laser system. Three of the four samples failed to build due to peeling off the plate due to dissimilar metals. This has been corrected for by switching to Ti-6Al-4V build plates. The surviving part has been sent for sectioning and will be used to determine initial density. Parameters will be adjusted accordingly to achieve the highest density possible.

2.1.2.12.3 Future Work. Work will continue to find the correct general parameters, build plate materials, and build settings that yield satisfactorily dense (>99.5%) parts that will build to completion and followed by parameter optimization. Maintaining and honing our safety protocols around Ti-6Al-4V will continue.

### 2.1.3 NASA Engineering and Safety Center-Funded Task Description/Status

#### 2.1.3.1 Pyroshock Characterization of Composite Materials.

2.1.3.1.1 Description. Composite materials are being considered for incorporation into the evolved SLS vehicle to improve performance and affordability. The lighter materials increase the vehicle's payload capability.

This task evaluates composite materials to ensure they can withstand the stresses induced into the vehicle during launch and stage separation. Tests are performed where an explosive charge is placed on a metal or composite plate affixed to a composite material panel. The test setup is shown in figure 22. When the charge is initiated, a shockwave is sent through the composite panel. Studying the behavior of composites when the shockwave is transitioning through the material will allow creating a model to predict how it will withstand launch stresses and shock loads.

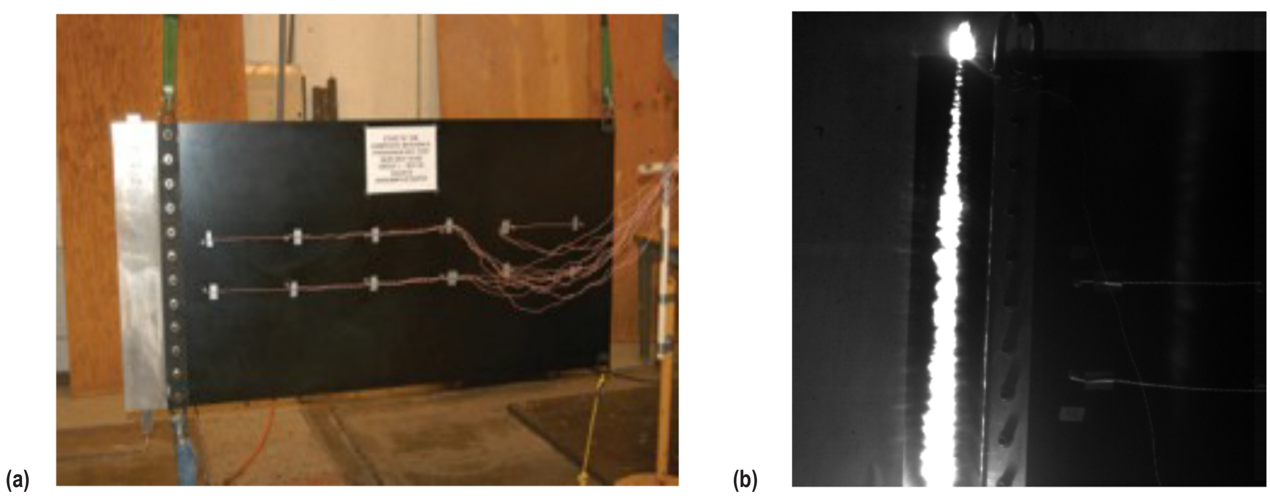



Figure 22. Pyroshock test setup: (a) Test article and (b) test.

2.1.3.1.2 Accomplishments. Significant achievements included completing all 28 of the task assessment baseline composite pyroshock tests, which included 10 monolithic composite panel tests (plus four retests) and 18 sandwich composite panel tests. In addition, algorithms were developed to analyze the shock data and statistical analysis was completed on the output from the algorithms for the monolithic composite panels.

2.1.3.1.3 Future Work. Testing of composite panels with and without melamine acoustic dampening foam began in 2014. The shock data from these tests will be qualitatively compared to evaluate the effect the addition of acoustic foam has on shock transmissibility in the composite materials. Analysis of the sandwich composite panel test data will be concluded by the second quarter of FY 2015.

**2.1.3.2 Booster Interface Loads.**

2.1.3.2.1 Description. The interaction between shock waves and the wake shed from the forward booster/core attach hardware results in unsteady pressure fluctuations, which can lead to large buffeting loads on the vehicle. This task investigates whether computational tools can adequately predict these flows, and whether alternative booster nose shapes can reduce these loads. Results from wind tunnel tests will be used to validate the computations and provide design information for future SLS configurations.

The current work combines numerical simulations with wind tunnel testing to predict buffeting loads caused by the boosters. Variations in nosecone shape, similar to the Ariane 5 design (fig. 23), are being evaluated with regard to lowering the buffet loads. The task will provide design information for the mitigation of buffet loads for SLS, along with validated simulation tools to be used to assess future SLS designs.

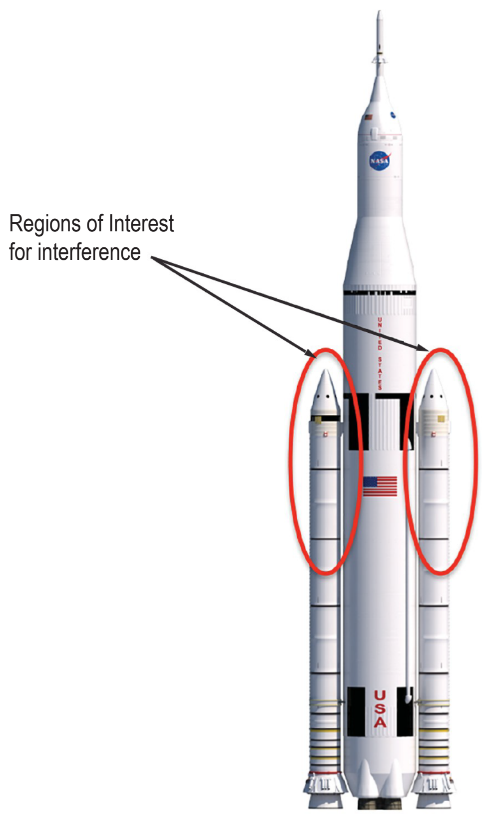




Figure 23. Booster interface loads.

2.1.3.2.2 Accomplishments. The project has completed an initial set of CFD cases covering six booster nose configurations for two Mach numbers and two angles of attack. These configurations were tested in the NASA Ames Research Center's 11-ft Transonic Wind Tunnel as part of an SLS aeroacoustic test. Both computationally predicted and measured wind tunnel results indicate that substantial improvement in the booster attach region environments can be achieved (fig. 24).

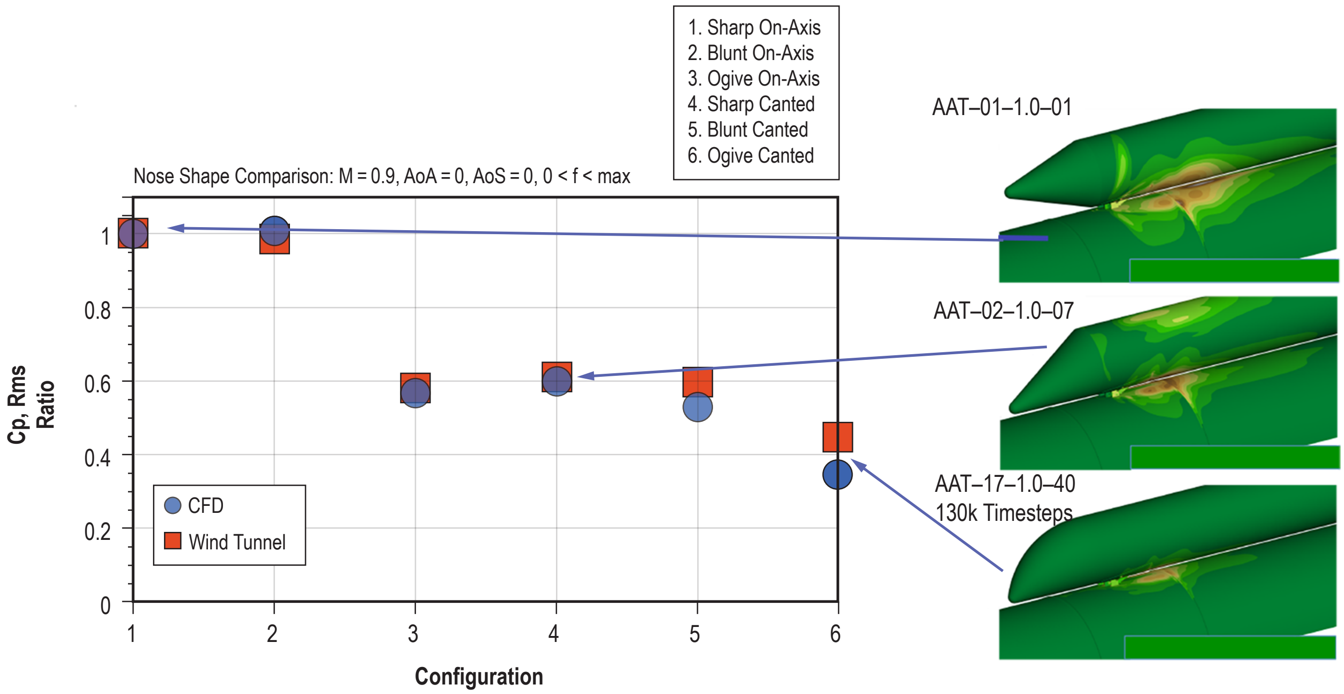



Figure 24. Area-weighted rms pressure levels in booster attach region.

While encouraging, overall root mean square (RMS) pressure levels are a relatively high level comparison. For combined load analysis, buffet-forcing functions, or integrated loads at a given longitudinal station, are needed. Accurate prediction of these buffet-forcing functions requires agreement in both magnitude and frequency. Figure 25(a) shows the computed and measured integrated load over a section of the core downstream of the forward attach point. Figure 25(b) is the corresponding power spectral density (PSD) in the frequency domain. As can be seen, the CFD currently underpredicts the magnitude and shifts the frequency.

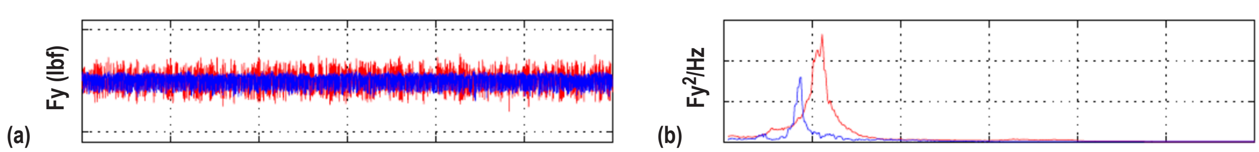



Figure 25. Integrated load and corresponding frequency domain PSD: (a) Integrated force and (b) PSD.

2.1.3.2.3 Future Work. In the next phase of this task, a small set of CFD solutions will be obtained to complement a recently conducted rigid buffet model test in the NASA Langley Transonic Wind Tunnel. Lessons learned from the previous CFD effort will be applied, with the goal of accurately predicting the buffet-forcing functions. The end result of this work will be the validation of a CFD code for numerical buffet simulation, which will be generally applicable to any future launch system.

**2.1.3.3 Advanced Booster Composite Case/Polybenzimidazole-Nitrile Butadiene Rubber Insulation Development.**

2.1.3.3.1 Description. The NESC was requested to examine processing sensitivities (e.g., cure temperature control/variance, debonds, density variations) of PBI-NBR insulation, case fiber, and resin systems and to evaluate NDE and damage tolerance methods/models required to support human-rated composite motor cases. The proposed use of composite motor cases in Block 2 is expected to increase performance capability through optimizing operating pressure and increasing propellant mass fraction. This assessment supports the evaluation of risk reduction for large booster component development/fabrication, NDE of low mass-to-strength ratio material structures, and solid booster propellant formulation as requested in the SLS NASA Research Announcement for Advanced Booster Engineering Demonstration and/or Risk Reduction. Composite case materials and high-energy propellants represent an enabling capability in the Agency's ability to provide affordable, high-performing advanced booster concepts.

The NESC team was requested to provide an assessment of co- and multiple-cure processing of composite case and PBI-NBR insulation materials and evaluation of high-energy propellant formulations. The assessment objectives included the following:

- Evaluate co- and multiple-cure processing studies through tensile strength, impact peel strength, and water burst testing:
  - Oven cure co-cure prepreg.
  - Oven cure multiple-cure prepreg.
  - Oven cure co-cure wet wind.
  - Oven cure multiple-cure wet wind.
  - Autoclave cure co-cure prepreg.

- Develop NDE damage standards by evaluating the impacts of composite case/PBI-NBR cylinders.

- Evaluate NDE techniques on subscale composite bottles to determine inspection methods best suited to large-scale loaded motors.

- Utilize NDE techniques to evaluate processing studies of composite case and insulation system.

- Evaluate high-energy propellants for burn rate, mechanical properties, and safety requirements for advanced booster concepts at the Army AMRDEC.

- Utilizing AMRDEC, manufacture established liner systems that are compatible with the high-energy propellants that are being evaluated.

2.1.3.3.2 Accomplishments. The following accomplishments were made:

- Hydroxyl terminated polybutadiene (HTPB) and hydroxyl terminated polyether (HTPE) propellant mixes (fig. 26) made at 1 pint, 1 gallon, and 5 gallon sizes:
  – Laboratory hazard testing complete and results acceptable.
  – End-of-mix viscosity acceptable.
  – Burning rate and pressure slopes acceptable. Can be modified to meet program requirements.
  – HTPE tensile properties acceptable.
  – HTPB formulation being worked to improve tensile properties.

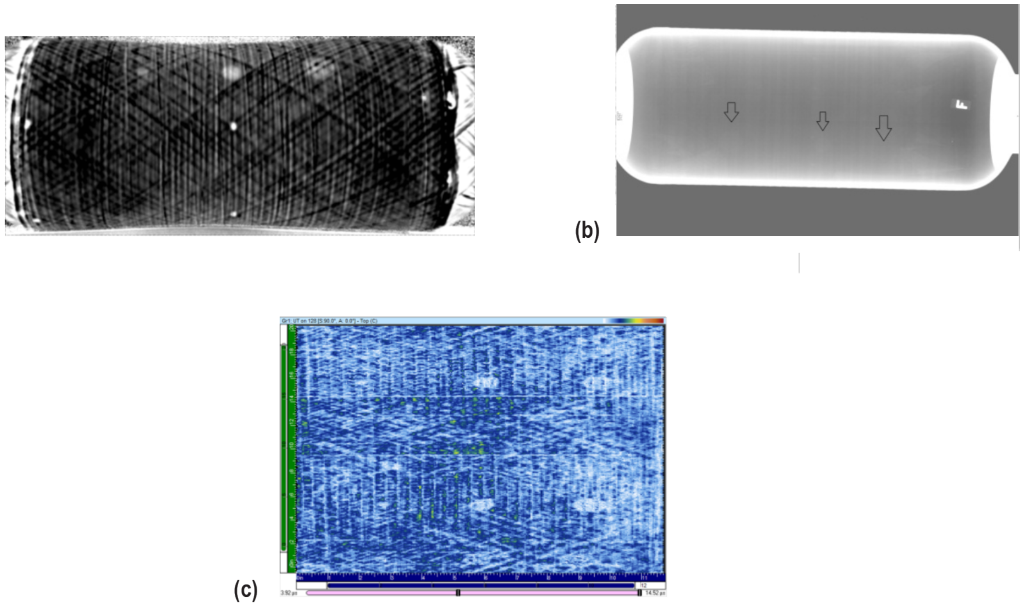
Figure 26. Propellant mixing at AMRDEC.

- Ablative liner mixes made at 1 pint and 1 gallon sizes:
  – End-of-mix viscosities acceptable.
  – Tensile properties acceptable.

- Kevlar®-Filled Ethylene Propylene Diene Monomer (KF-EPDM) downselected as insulation for bond line evaluations.

- Accelerated aging of HTPE propellant and its bond line specimens has commenced.

- Forty-five bottles manufactured and NDE complete (fig. 27).
  – Eight test bottles and one defect standard—prepreg co-cure in an oven.
  – Eight test bottles and one defect standard—prepreg multiple-cured in an oven.
  – Eight test bottles and one defect standard bottle—wet wound and co-cured in an oven.
  – Eight test bottles and one defect standard bottle—wet wound multiple-cured in an oven.
  – Eight test bottles and one defect standard bottle—prepreg co-cured in an autoclave.

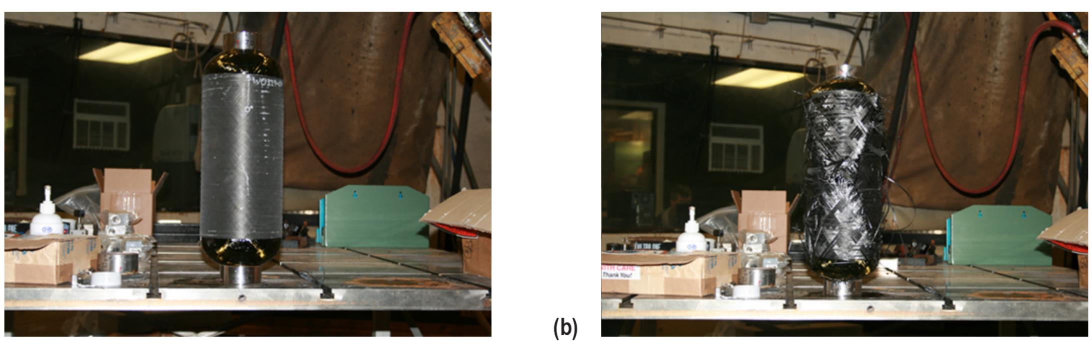


(a) (b) (c)

Figure 27. Defect standard analyzed using various NDE techniques: (a) Infrared flash thermography, (b) radiography, and (c) ultrasonic testing.

- Impact trials conducted to determine lower bound on detectable damage via NDE.

- Burst testing of bottles performed (fig. 28) to evaluate possible differences in structural capability of different processing methods. Comparison in burst pressures of the pristine co-cure and pristine multiple-cure bottles do not reveal a visible difference in burst strength.



(a) (b)

Figure 28. Bottle burst test: (a) Bottle prior to burst and (b) bottle after burst test with failure in hoop.

- NDE techniques evaluated:
  – Infrared flash thermography (IRT) has proved to be an excellent method for finding indications.
  – Radiography (RT) has been successful in finding inserts in defect standards.
  – Computed tomography (CT) is unable to find inserts in defect standards or indications found by IRT but has been excellent in detecting thickness and density changes.

2.1.3.3.3 Future Work. Future work includes the following:

- Further evaluate HTPB formulation for improved mechanical properties at high solids loading (90%).

- Scale-up optimized HTPB formulation for propellant and bondline accelerated aging.

- Continue HTPE formulating to evaluate burning rates through strands and subscale motors.

**2.1.3.4 Advanced Booster Combustion Stability.**

2.1.3.4.1 Description. Combustion instability is a phenomenon in liquid rocket engines caused by complex coupling between the time-varying combustion processes and the fluid dynamics in the combustor. Consequences of the large pressure oscillations associated with combustion instability often cause significant hardware damage and can be catastrophic. The current combustion stability assessment tools are limited by the level of empiricism in many inputs and embedded models. This limited predictive capability creates significant uncertainty in stability assessments. This large uncertainty then increases hardware development costs due to heavy reliance on expensive and time-consuming testing.

The objectives of this task are to advance the predictive capability of state-of-the-practice combustion stability methodologies and tools used for the SLS injector combustion stability assessment, facilitate more confident identification and characterization of combustion instabilities and efficient mitigation during SLS propulsion system development, and minimize SLS development costs and improve hardware robustness.

2.1.3.4.2 Accomplishments. The following tasks have been accomplished:

- Injector element design, scaling, testing, and CFD simulation:
  - Element 1b (baseline element):
    - Testing is complete at both the Air Force Research Laboratory (AFRL) (full-scale at 350–1,100 psia) and Purdue (subscale at 450 psia).
    - CFD analyses of both elements is complete.
    - Testing and CFD analysis at both scales showed an ≈180 Hz chug instability.
  - Element 1b4:
    - This is a redesign of element 1b to eliminate the chug instability.
    - Testing at AFRL is complete; both testing and CFD analysis indicate chug is still present, but at a considerably lower amplitude.
  - Element 1b5:
    - This redesign of element 1b4 is being fabricated for testing at both AFRL and Purdue.
    - CFD simulations indicate it should be stable.

- Demonstration of new capabilities on SLS ABEDRR injector:
  - Three-dimensional reacting flow CFD simulations of a seven-element representation of the ABEDRR injector have been completed (figs. 29 and 30).
  - Data extracted from CFD simulations used to augment engineering stability assessment tools see (figs. 31 and 32).

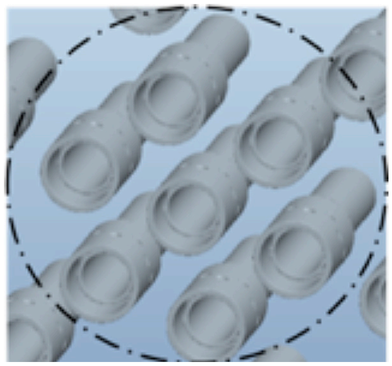


Figure 29.  Seven elements from an ABEDRR injector.

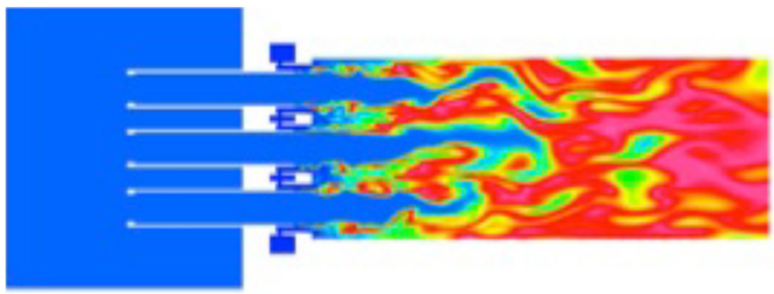


Figure 30.  Two-dimensional cut of temperature field of seven-element injector.

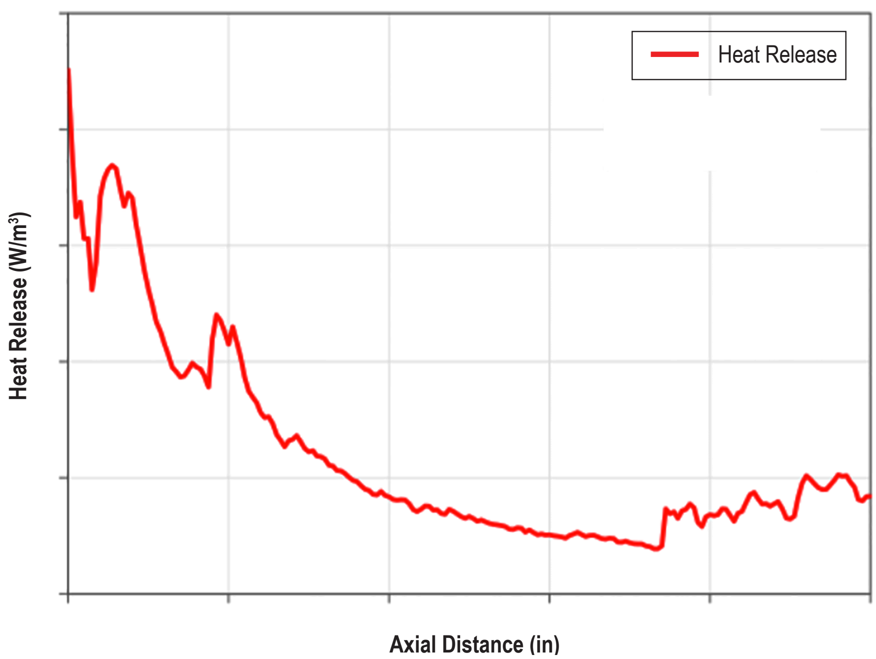



Figure 31.  Heat release profile from CFD simulations.

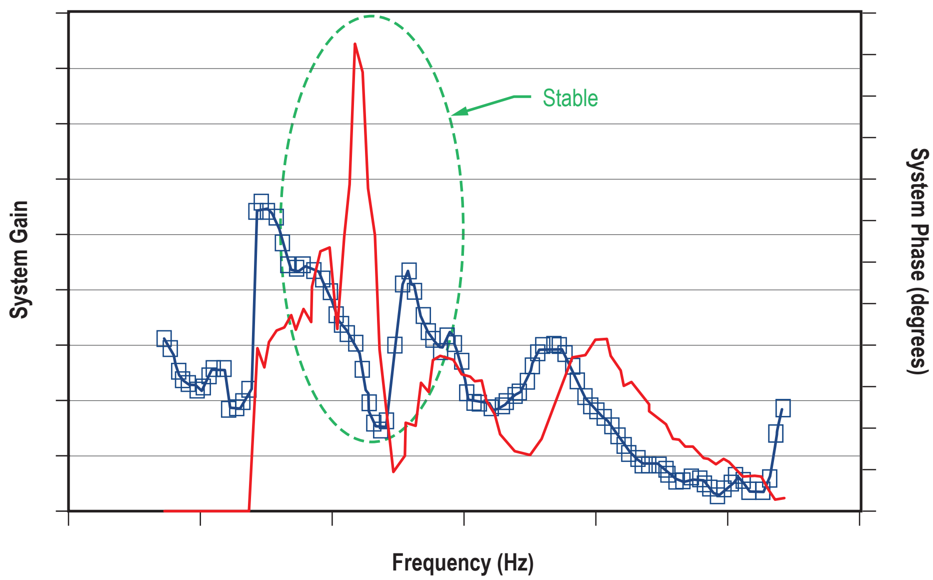



Figure 32. Stability plot generated with input from CFD analysis.

2.1.3.4.3 Future Work. Plans for future work include the following:

- Testing of element 1b5 at both AFRL and Purdue.
- CFD simulations of element 1b5.
- Stability assessments of element 1b5 both with and without inputs from CFD to the engineering assessment tools.

## 2.2 Academia Contracts/Grants

The nine academic grants awarded in early 2013 were all extended with one-year options and will be evaluated in late 2014 to determine if funding and performance allow for exercising the final option year. Two additional grants were added in FY 2014 to the University of Florida and Mississippi State University. The new tasks have a base year and the possibility of one option year. The geographical distribution is shown in figure 33.

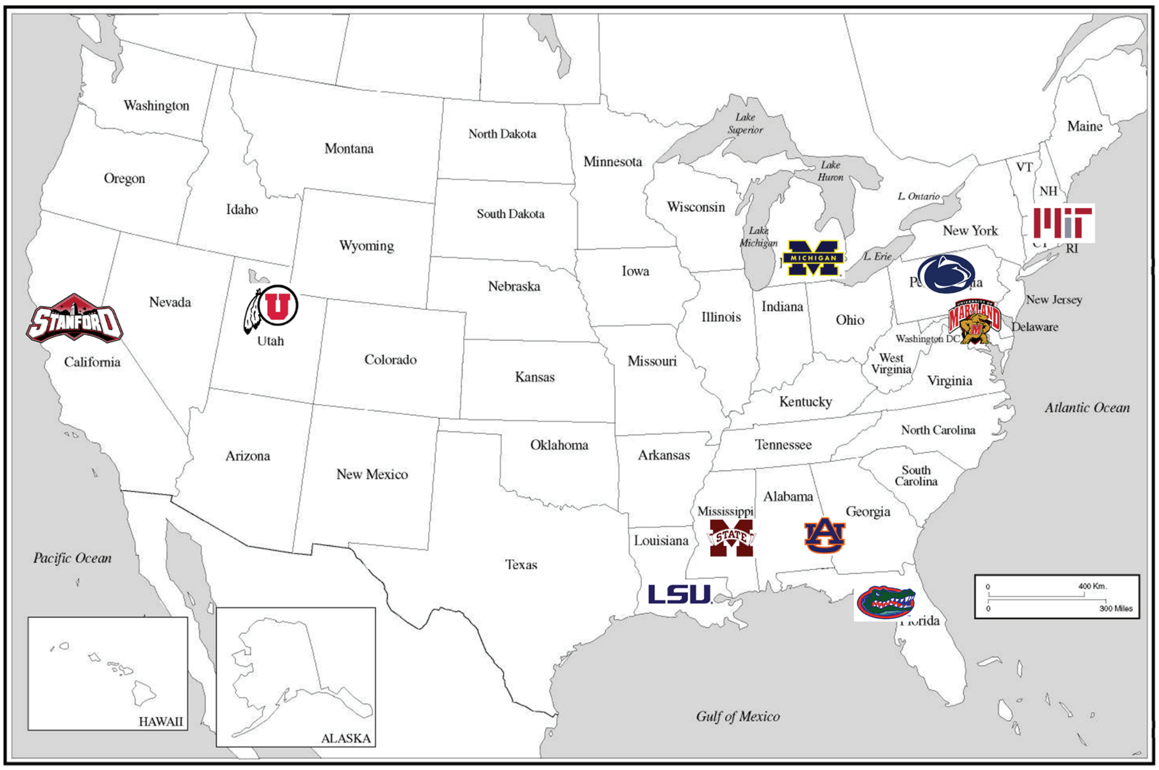



Figure 33. Academia contracts/grants for geographical distribution in the United States.

Five of the eleven grants deal with improving or utilizing the Loci family of CFD/finite element modeling codes. Loci is a C++ library and declarative programming framework that efficiently maps numerical algorithms onto parallel architectures. The approach is logic based so that it allows a description of what the code should accomplish, but it does not dictate how to accomplish it (as in imperative programming). Loci is thus a flexible, rule-based programming model for numerical simulation that allows runtime scheduling of the appropriate subroutine calls required to obtain a user-specified goal.

The Loci family of codes was developed in 1999 by a National Space Foundation funded effort. The architecture was designed at Mississippi State University. The framework and most of the modules are open access; however, there are some modules with ITAR restrictions. These codes are designed such that very large simulations can be run efficiently on multiple processors utilizing

supercomputers (e.g., the ARC Pleiades supercomputer). The overall framework is such that the codes are conducive to independent/third party module development resulting in development and implementation of multiple high-fidelity modules. Loci currently has the following four major areas:

(1) Loci/CHEM (most mature and developed first):
- Advanced turbulence, heat transfer, structural analysis, and droplet models.
- Nonideal equations of states found in high-pressure environments.
- Overset meshes for complex geometry and object-in-motion problems.

(2) Loci/STREAM (originally developed at the University of Florida, funded by MSFC 2004–present):
- Geometric complexity using unstructured or moving grids.
- Real-fluid modeling for cryogenic propellants.
- Unsteady cavitation, multiphase flows, and flamelet models.

(3) Loci/BLAST (relatively new CFD code funded by the U.S. Army):
- Modeled blast-soil interactions (landmines buried in sand).
- Modeled the structural effects of blast on vehicles.
- Validated for blast events that would simulate failed motor ignition on test stand.

(4) Loci/THRUST (research):
- CFD code for acoustic modeling.

Sections 2.2.1 through 2.2.11 provide a brief overview of each of the grants.

### 2.2.1 High Electrical Energy Density Devices for Aerospace Applications (Auburn University)

#### 2.2.1.1 Principals:

- Principal investigator (PI): Z.Y. Cheng, Ph.D.
- Co-PI: B.A. Chin, Ph.D.
- MSFC technical monitors (TMs): Jeff Brewer and Terry Rolin

**2.2.1.2 Description.** This effort is to develop a database of the characteristics and specifications of commercially available electrical energy devices and to experimentally determine the characteristics and specifications of these devices. Additional activities include:
- Using different electrical loads to simulate different applications in aerospace environments.
- Identifying the most promising candidates for use on space vehicles.
- Identifying emerging technologies in the energy storage device discipline and their potential applications.

This task was expanded slightly in 2014 to take advantage of a synergistic in-house activity concentrating on ultracapacitors. Working cooperatively and utilizing Auburn's unique material testing capabilities, both efforts benefitted greatly.

### 2.2.2 Challenges Towards Improved Friction Stir Welds Using Online Sensing of Weld Quality (Louisiana State University)

#### 2.2.2.1 Principals:

PI: Muhammad Wahab, Ph.D.
MSFC TM: Arthur Nunes, Ph.D.

**2.2.2.2 Description.** This activity will develop an online real-time system to determine weld quality for friction stir welds. The overall effort is depicted in figure 34.

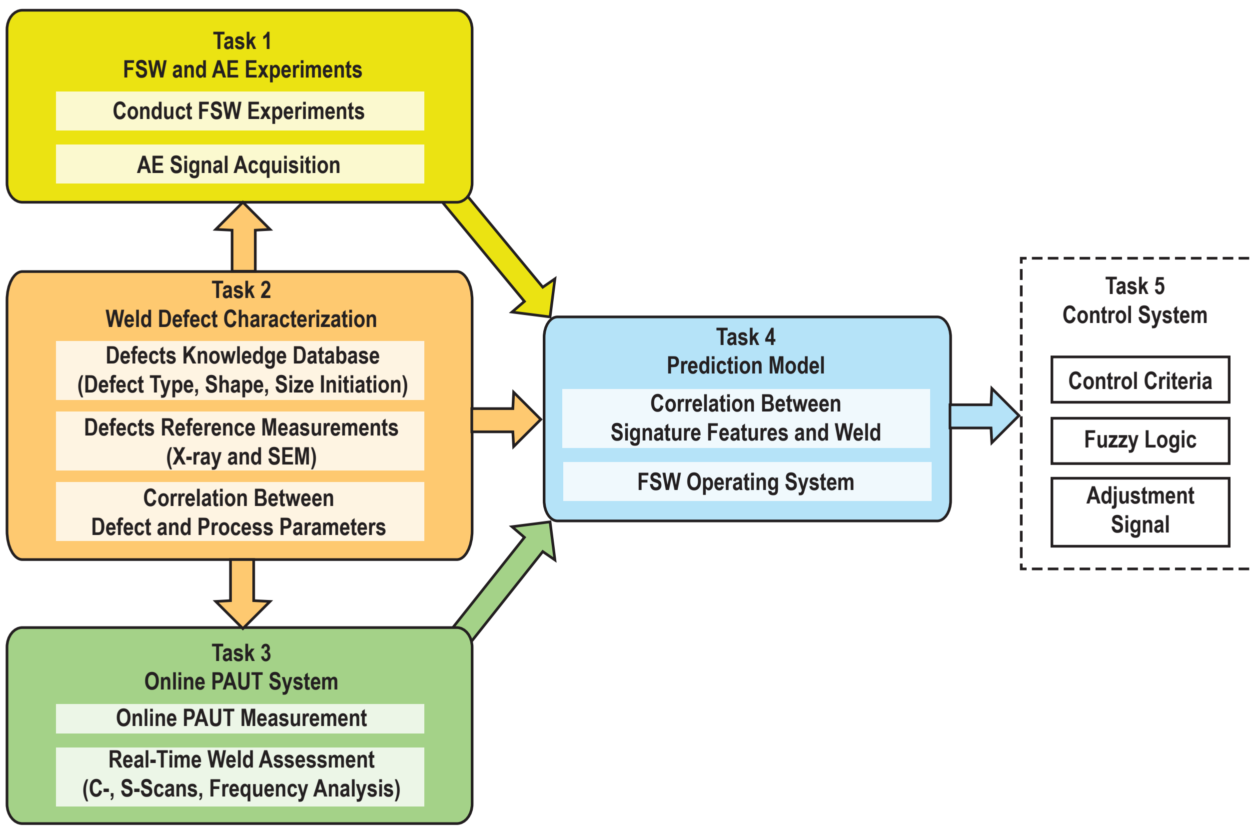



Figure 34. LSU activity flow chart.

The detection of defects as they form during FSW enables online repair and/or avoidance of defects. Four issues are being analyzed including defect regions, temperature during FSW, fracture surface and Systems Engineering Management (SEM) analysis, and fracture-origination detection methods. If successful, this tool may ultimately eliminate or reduce unforeseen or sudden failures in lightweight welded structures, increase cost-effectiveness, and decrease risk.

### 2.2.3 A New Modeling Approach for Rotating Cavitation Instabilities in Rocket Engine Turbopumps (Massachusetts Institute of Technology)

#### 2.2.3.1 Principals:

PI: Z. Spakovszky, Ph.D.
MSFC TMs: Andrew Mulder and Thomas Zoladz

**2.2.3.2 Description.** This activity will develop a new methodology (referred to as body force modeling) for quickly assessing inducer designs for cavitation instabilities (fig. 35) by leveraging a recently developed method for similar analyses on jet engine compressors. A known geometry, pseudo-RS-25 low-pressure oxidizer pump (LPOP), will be used to benchmark the methodology.

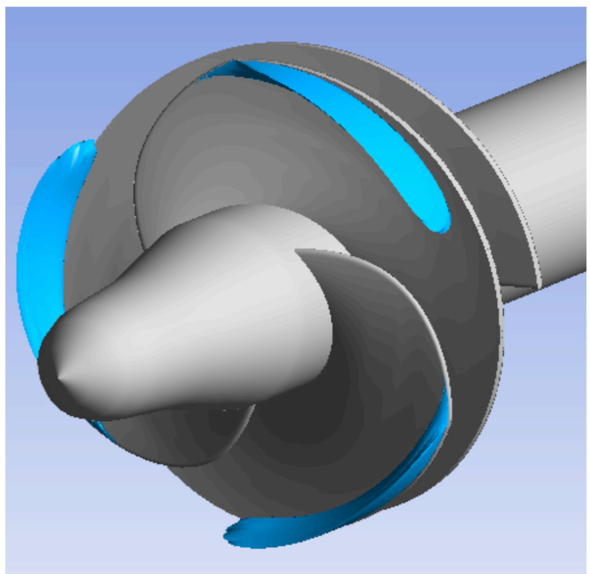


Figure 35. Inducer rotating cavitation instabilities.

The pseudo-LPOP inducer has been designed, fabricated, and was tested this year in The Aerospace Corporation's water flow test facility. Results from the test will provide a baseline for validation of the body force methodology.

Notable progress has been made in creating the analytical framework for body force modeling of a cavitating rocket engine inducer. This has required some modifications to the traditional body force model method to account for the complex flow environments generated by the design features of modern liquid rocket engine turbomachinery.

Mitigation of cavitation instabilities in SLS turbomachinery (RS-25 LPOP and low-pressure fuel pump (LPFP), J2-X LOX pump) will improve rocket engine reliability and performance. Any liquid propulsion system would benefit from this tool.

### 2.2.4 Low Dissipation and High Order Unstructured Computational Fluid Dyamics Algorithms to Complement the Use of Hybrid Reynolds-Averaged Navier Stokes/Large Eddy Simulation Algorithms (Mississippi State University)

#### 2.2.4.1 Principals:

PI: Keith Walters, Ph.D.
Co-PI: Ed Luke, Ph.D.
MSFC TM: Chris Morris, Ph.D.

**2.2.4.2 Description.** This activity will develop a new methodology to predict loads (steady and unsteady) and heating for the SLS vehicle by using a hybrid Reynolds-averaged Navier Stokes (RANS)/large eddy simulation (LES) approach to directly capture turbulent fluid motion in parts of a simulation. This will significantly improve CFD predictions (fig. 36) for the following:

- Rocket engine exhaust plumes and associated acoustic noise.
- Vehicle base flows, plume interactions, and recirculation.
- Flow over vehicle protuberances and associated acoustic noise.

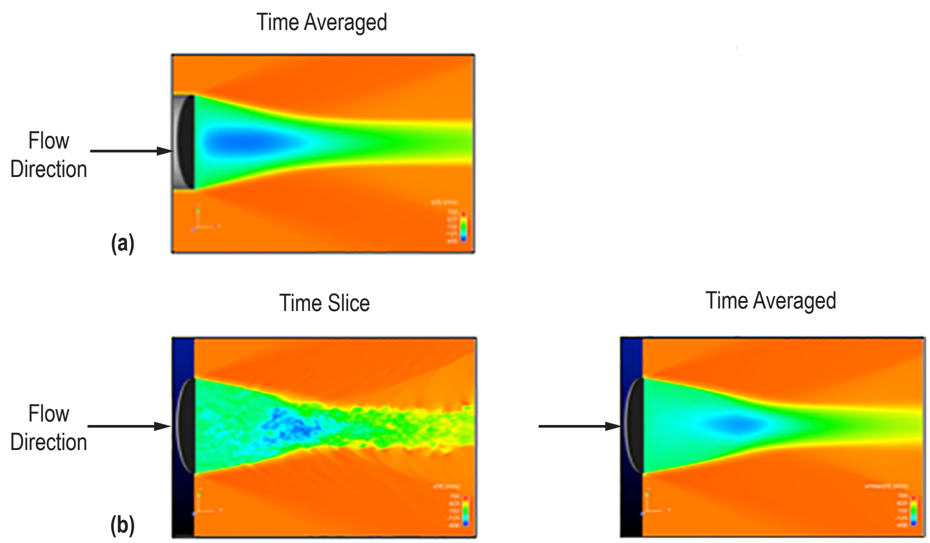



Figure 36. Fluid motion: (a) Current capability versus (b) improved simulation techniques.

The current hybrid RANS/LES capability in the Loci/CHEM code is suboptimal and has been identified for several years as an area that needs improvement. An improved prediction capability of loads on the SLS vehicle and components will enable higher fidelity environments definition, resulting in a more efficient design. Year one of this task focused on initial implementations of two numerical methods in Loci/CHEM that result in improved capturing of unsteady and turbulent flow physics. Work in year two has resulted in stability improvements to these new methods, and development and testing of an improved dynamic hybrid RANS/LES turbulence model is also underway.

### 2.2.5 Next Generation Simulation Infrastructure for Large-Scale Multicore Architectures (Mississippi State University)

#### 2.2.5.1 Principals:

PI: Ed Luke, Ph.D.
MSFC TM: Jeff West, Ph.D.

2.2.5.2 Description. Very large-scale simulations are required to obtain accurate, high-fidelity physics-based models of the SLS. These simulations are an integral part of modern engineering and design processes and are important tools for determining risks to design objectives posed by highly complex phenomena associated with vehicle level concerns, such as launch and flight characterization as well as component level concerns, such as modeling rocket combustion chambers and propellant feed systems. The highest fidelity of these models such as those used for acoustic or large eddy simulations can require extremely large meshes which will be run on very large, massively parallel computer systems. The main goal of this project is to significantly advance the already high scalability of the Loci system to facilitate extreme scales that these advanced models will require. The scalability improvements addressed by this project are two-fold:

(1) Next generation systems will be composed of very large numbers of computational cores (100 cores) arranged in high core density nodes composed using large, tightly coupled communication networks. Thus, the next generation of systems will be able to provide 100,000 cores by combination of thousands of nodes with each node consisting of hundreds of cores. For such systems, the use of message passing interface (MPI) alone will not be practical to exploit this parallelism because there are fundamental overheads associated with MPI that, while small, are on the order of the number of cores managed by the MPI system. At 100,000 cores, these costs become significant. To solve this problem, this project is creating an efficient hybrid thread plus an MPI scheduling approach that can significantly reduce these MPI costs by reducing the number of processes that MPI manages to the number of nodes rather than the number of cores.

(2) The second scaling concern is that such large processing systems will allow for simulations of meshes that are composed of many billions of elements. Unfortunately, the current implementation of Loci utilizes 32 bit integers to index entities that it manages which, unfortunately, limits the number of entities that Loci can manage to 2 billion, consequently limiting mesh sizes to about 1/2 billion elements (because each element requires many entities to describe). So the second goal of this task is to raise this limit. A naive approach to raise this limit would be to uniformly increase the number of bits that is used for all integers, but this would produce severe performance degradation. Therefore, the proposed approach uses a sophisticated scheduling approach that manages data such that this scale can be increased without imposing performance costs.

Significant accomplishments have been achieved over the 7-month period that this task has been active. A few highlights of the accomplishments are as follows:

(1) The implementation of a prototype hybrid thread scheduler for Loci is complete.

(2) A comprehensive characterization of the thread parallelism inherent to the Line Symmetric Gauss Seidel Linear System Solver (LSGS) used by many Loci codes has been performed.

(3) A robust vectorization strategy for the LSGS solver has been developed.

(4) Extension of the scale of entities managed by the Loci system has been increased from 2 billion to 4 billion entities, enabling a doubling of the scale of simulations that can be performed by Loci codes.

Note, the current prototype thread scheduler for Loci is not compatible with the production codes, but is expected to be fully compatible with production codes in the next few months. Some performance degradation has been observed with the thread scheduling compared to MPI scheduling on small numbers of nodes. Optimizing the performance of the thread schedule is one of the second year deliverables of this project.

### 2.2.6 Development of Subcritical Atomization Models in the Loci Framework for Liquid Rocket Injectors (University of Florida)

#### 2.2.6.1 Principals:

PI: Siddharth Thakur, Ph.D.
Co-PI: Mrinal Kumar, Ph.D.
MSFC TM: Jeff West, Ph.D.

**2.2.6.2 Description.** This study is the precursor for advancement in our understanding of combustion instabilities and determination of heat transfer coefficients for two-phase flows of cryogenic propellants during line chilldown and fluid transport (fig. 37). Both steady and unsteady atomization will be addressed.

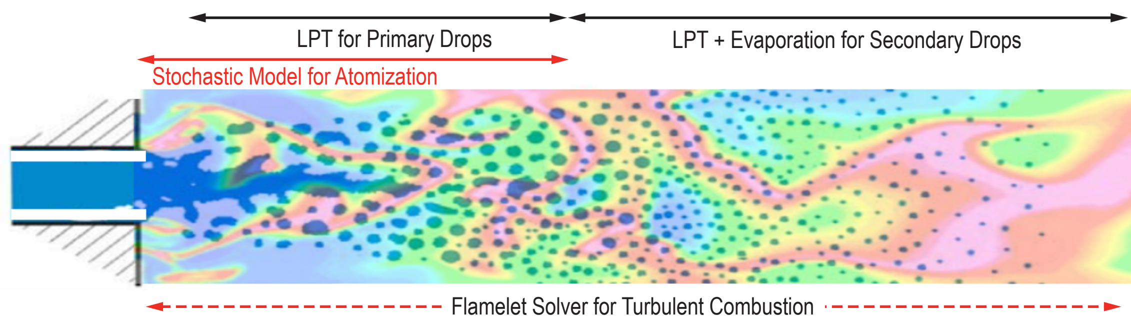



Figure 37. Injector subcritical atomization simulation.

In the current year, the Monte Carlo approach is being extended to the transient analysis of unsteady atomization. Initial simulation results capturing the time-varying probabilistic distribution of the intact liquid core have been obtained. In addition, the developed unsteady models have been assimilated into the LOCI/STREAM framework and coupled with the background flow solver. Current work is being carried out to include time-varying probabilistic models for droplet size, velocity vector at release, and temperature.

This activity will ultimately result in a model that enables better understanding of the critical physics in SLS liquid propulsion systems, improved combustion efficiency, the development of higher fidelity designs for injectors, and the reduction of environment uncertainty.

### 2.2.7 Determination of Heat Transfer Coefficients for Two-Phase Flows of Cryogenic Propellants During Line Chilldown and Fluid Transport (University of Florida)

#### 2.2.7.1 Principals:

PI: J.N. Chung, Ph.D.
MSFC TM: Alok Majumdar, Ph.D.

**2.2.7.2 Description.** When any cryogenic system is initially started, this includes, rocket thrusters, turbo engines, reciprocating engines, pumps, valves, and transfer lines, it must go through a transient chilldown period prior to steady operation. Chilldown is the process of introducing the cryogenic liquid into the system, and allowing the hardware to cool down to several hundred degrees below the ambient temperature. The chilldown process is anything but routine and requires a proper engineering design to chill down a cryogenic system in a safe and efficient manner. The heat transfer characteristics associated with the transfer line chilldown, and propellant transfer, loading and recirculation in feed subsystems of the SLS, are crucial information for the design and proper operation of these cryogenic transport processes.

The general scope of the project is to acquire sufficiently detailed experimental data in both terrestrial and microgravity conditions for characterizing heat transfer coefficients in two-phase flows of cryogenic propellants (using $LN_2$ as a simulant) with and without ingested helium gases. The heat transfer coefficients in the form of empirical correlations will be incorporated in a computer simulation code for the Propulsion System Model for characterizing the thermal environment in feed systems for chilldown of cryogenic transfer lines and propellant transfer, loading, and recirculation. Tests will be conducted over a pressure range from 20 to 70 psia, 2,000 < Reynolds Number (Re) < 100,000 and 1.75 < Prandtl Number (Pr) < 2.3. A detailed uncertainty analysis will be provided and the data will be presented with appropriate error bars.

Currently, at the end of 7 months in the first year of the project, an experimental database for all the cases without ingested helium has been successfully completed. An experimental system has been modified for the inclusion of helium ingestion effects and some preliminary runs have been achieved. Correspondingly, data analysis and heat transfer coefficient empirical correlation development have been proceeding in parallel. Correlation models have been determined and their fittings with the experimental results are under evaluations.

### 2.2.8 Validation of Supersonic Film Cooling Numerical Simulations Using Detailed Measurement and Novel Diagnostics (University of Maryland)

#### 2.2.8.1 Principals:

PI: Chris Cadou, Ph.D.
MSFC TM: Joe Ruf

**2.2.8.2 Description.** This activity is developing a numerical methodology and experimental datasets to enable validation of fluid dynamics simulations of supersonic film cooling (SSFC). The experiment portion of this effort includes laboratory scale SSFC experiments that are scaled from the J-2X nozzle extensions environments. Detailed measurements of heat flux and pressures have been made for multiple film coolant flow rates. Work continues to implement novel diagnostics such as focused Schlieren imaging, Schlieren image-based particle velocimetry, and automated image interrogation. The fast-acting light source and alignment framework for the focused Schlieren imaging have been constructed. On the numerical methodology portion of the task, many parametric analysis with a high-fidelity LES fluid dynamics code have been performed to assess the effects of different boundary conditions and assumptions on the simulation of SSFC. Work has begun to incorporate the lessons learned into fluid dynamic simulations implementing MSFC's workhouse fluids code, Loci/CHEM.

SSFC (fig. 38) is used on the J-2X nozzle extension to protect the extension from the much hotter primary flow. Significant conservatism had to be included in the J-2X nozzle extension design to account for the uncertainty on the effectiveness of the SSFC as calculated with fluid dynamics codes. Improvement in these fluid dynamics codes, ability to define the environments, and effectiveness of SSFC could result in significant savings of resources in the design cycle for the next nozzle that uses SSFC.

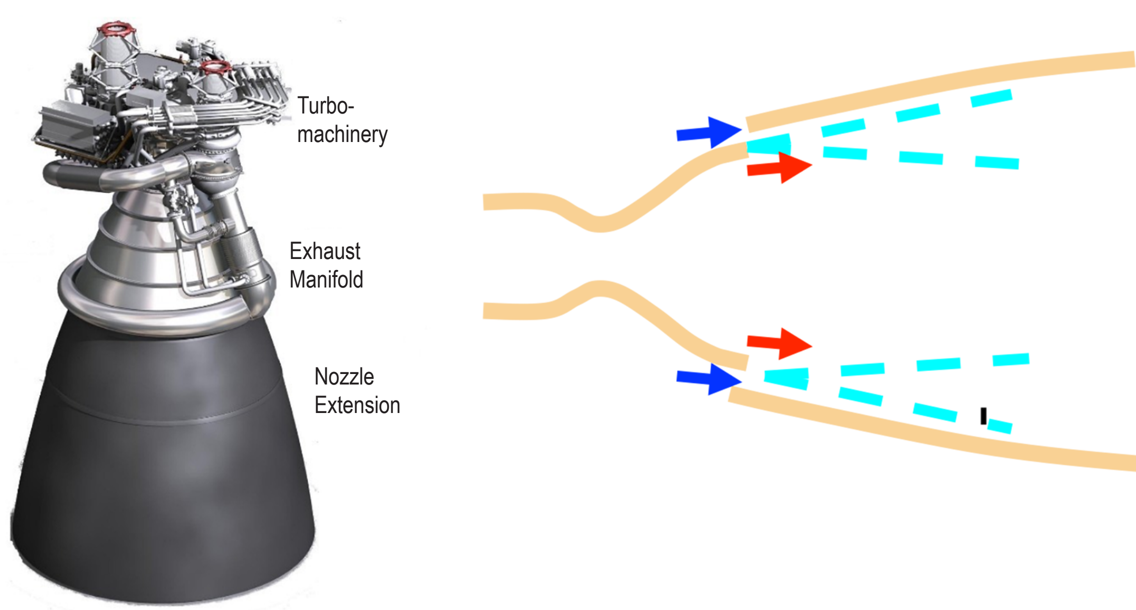



Figure 38. J-2X film-cooled nozzle extension.

### 2.2.9 Advanced Large Eddy Simulation and Laser Diagnostics to Model Transient Combustion-Dynamical Processes in Rocket Engines: Prediction of Flame Stabilization and Combustion Instabilities (University of Michigan)

#### 2.2.9.1 Principals:

PI: Jim Driscoll, Ph.D., University of Michigan
Co-PI: Matthias Ihme, Ph.D., Stanford University
MSFC TM: Kevin Tucker

**2.2.9.2 Description.** This activity will develop a methodology to enable advanced LES and laser diagnostics to model transient combustion-dynamic processes in rocket engines. The following specific areas are being investigated:

- Predict flame stabilization and combustion instabilities (fig. 39).

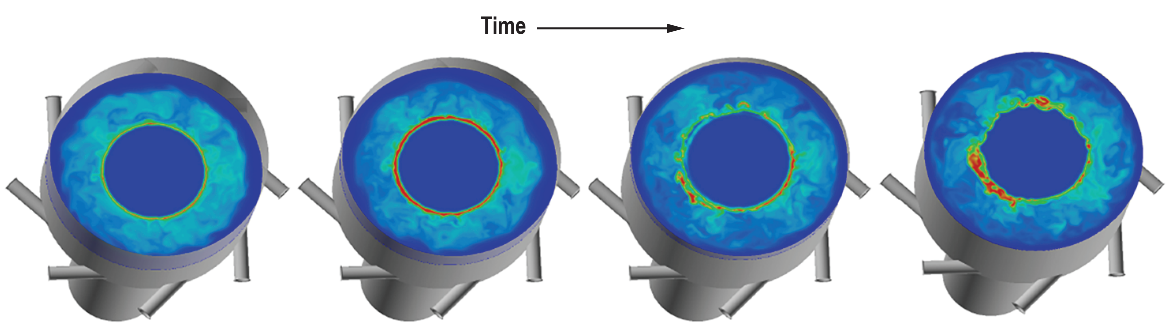



Figure 39. Unsteady burning in the cup of a coaxial element.

- Develop an adaptive combustion model that combines computationally efficient flamelet-based combustion models with a detailed chemistry formulation for the representation of complex combustion regimes that are associated with multidimensional flame base representation.

- Implement the new chemistry capability into Loci/STREAM.

- Acquire a comprehensive experimental database to enable systematic validation of high-fidelity combustion models.

- Validate the new capability in Loci/STREAM using the experimental database.

Replacing empirically-based inputs with higher fidelity physics-based inputs in the combustion stability assessment process will provide improved injector performance and heat transfer predictions.

### 2.2.10 Characterization of Aluminum/Alumina/Carbon Interactions Under Simulated Rocket Motor Conditions (Pennsylvania State University)

#### 2.2.10.1 Principals:

PI: Kenneth Kuo, Ph.D.
MSFC TM: Matthew Cross, Ph.D.

**2.2.10.2 Description.** This activity is investigating the interaction of aluminum and alumina ($Al_2O_3$) with carbon in typical solid rocket motor (SRM) environments while considering realistic condensed phase residence times on carbon-containing insulation/nozzle materials surfaces. The primary goal is evaluation of the chemical reaction mechanism and approximate reaction rates between alumina and carbon. This effort utilizes multiple test rigs; within the past year this has included a low-pressure $CO_2$ laser sample heating chamber and a high-pressure induction furnace which is under development. Some of the highlights from the FY 2014 activities follows.

Laser heating experiments were conducted utilizing an Everlase S48 $CO_2$ laser capable of delivering ≈760 W continuously at Penn State's High-Pressure Combustion Lab (HPCL). The beam was augmented using a zinc/selenium (ZnSe) lens pair designed to reduce the diameter of the beam and a graphite mask (installed in a water-cooled copper block) to set the final beam diameter and remove the low power edges of the beam profile. A laser-transparent window assembly, consisting of a purged potassium chloride (KCl) window within a housing, allowed the augmented laser beam to pass into a low-pressure test chamber. A sample was then placed in the test chamber which was capable of maintaining either subatmospheric or up to 2-atm pressurized gas; either argon (Ar) or carbon monoxide (CO) was used in this test series. The sample consisted of a small graphite 'crucible' containing compressed $Al_2O_3$ and/or Al powder (1/4-in outside diameter (OD)) mounted on a 1/16-in OD hafnia rod ($T$melt = 3,031 K). During laser heating, the backside temperature was monitored with an HPCL custom-made, single-bead, 125-μm D-type tungsten-3% / rhenium (W-3%Re/W-25%Re) thermocouple, while the surface temperature was measured by the multicolor pyrometer. The temperature range used for these experiments were selected to be consistent with Al/$Al_2O_3$/carbon (C) reaction onset temperatures and those found on carbon-containing material surfaces inside an SRM.

Over the base year (overlapping with the initial months of FY 2014), 55 laser-heating experiments were conducted. Of those, 29 tests were considered in the nominal configuration with 100% $Al_2O_3$ in graphite crucible; 23 were conducted with Ar and 6 with CO atmospheres. In addition, eight were conducted with various $Al_2O_3$/Al mixtures. Other testing included graphite heating only, and 100% $Al_2O_3$ in vacuum. General behavior with temperature was observed with video, along with gas sampling and post-test sample analysis performed on select test samples. For these tests, two heating profiles were utilized: (1) Slow heating (30 to 40 K/s) to a particular temperature and hold for 120 s, and (2) slow ramping up to a high temperature with 5- to 10-s holds at ≈25 or 50 K increments. Sample temperatures over 2,500 K were examined. X-ray diffraction (XRD) with a microdiffractometer was utilized to examine a select number of post-heated samples. Figure 40 shows extracted video frames of a sample while heating, a photograph of collected particles which ejected from the sample while it was heating, a photograph showing the measurement location for

XRD, and the XRD diffraction pattern showing the presence of $Al_4C_3$ post-test. The effect of pressure was examined through a series of thermodynamic calculations for the relevant chemical reactions of interest (see fig. 41). This figure shows the response of three expected reactions: with increased SRM chamber pressure (i.e., higher CO partial pressure (PCO)), the reaction onset temperatures change significantly, and the most likely reactions shift order.

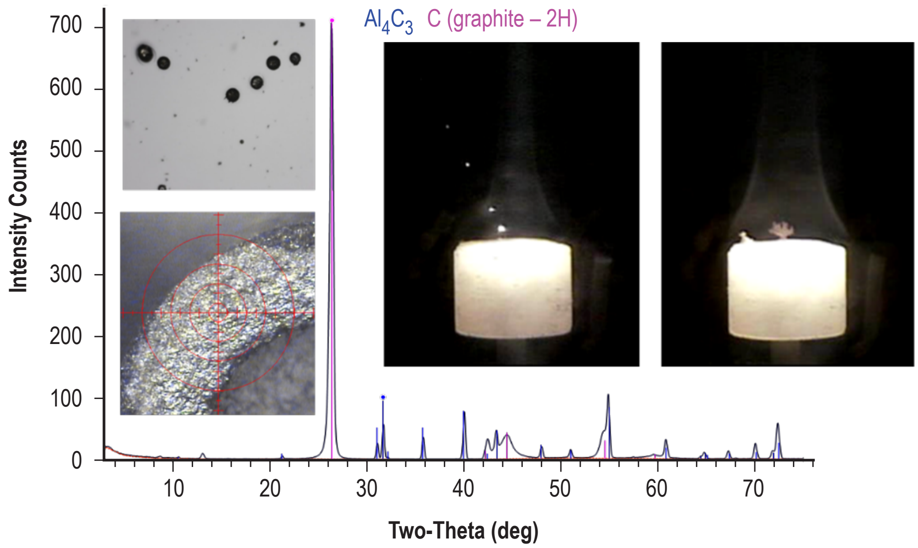



Figure 40. Images of graphite/$Al_2O_3$ sample heating and XRD diffraction pattern.

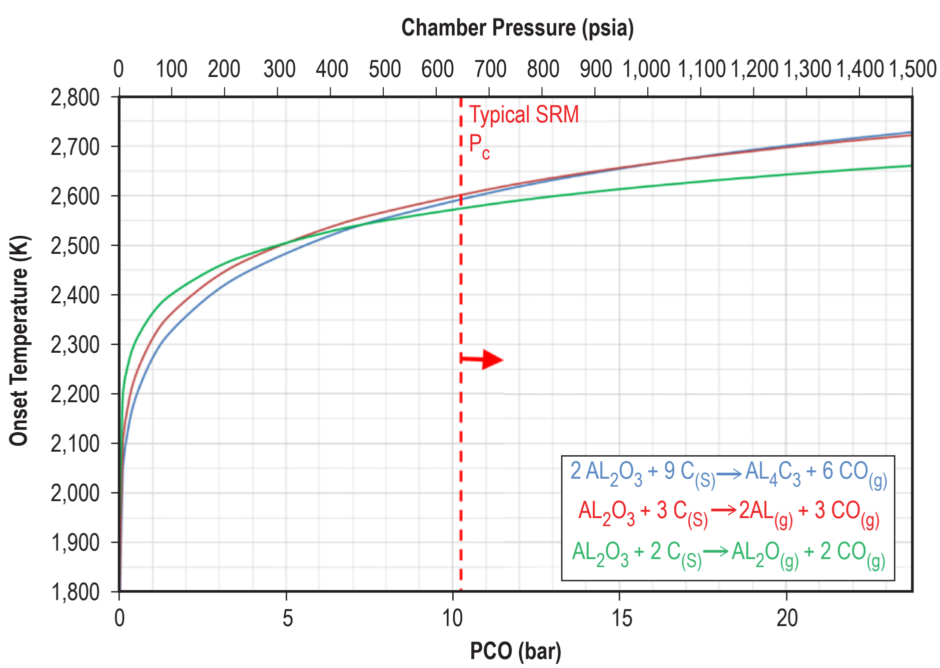



Figure 41. Onset temperature of several $Al_2O_3$/C reactions as functions of CO partial pressure and corresponding SRM chamber pressure.

Based upon the initial findings of FY 2014, the remaining portion of the year was dedicated to the development of a unique high-pressure, high-temperature induction furnace (1,000 psia and 2,700 K). This furnace will utilize induction heating of larger, well-mixed $Al_2O_3$/C samples within a graphite crucible. In addition to post-test sample analysis, online measurement of sample mass change and temperature will be performed. Teaming has begun with other Penn State researchers specializing in the development of phase diagrams, and in particular, the Al/C/oxygen (O) system, with the intent of extending the state-of-the-knowledge to pressures significantly higher than atmospheric (current limit of the literature).

In addition to the primary program tasks, support to the MSFC ER43 technical points of contact on related SRM research has continued, including carbon-cloth phenolic nozzle erosion studies utilizing real-time X-ray radiography (X-ray RTR), studies of SRM internal insulation, and advanced SRM total and radiative heat transfer diagnostics.

### 2.2.11 Acoustic Emission-Based Health Monitoring of Space Launch System Vehicles (University of Utah)

#### 2.2.11.1 Principals:

PI: V. John Mathews, Ph.D.
Co-PI: Dan Adams, Ph.D.
MSFC TM: Alan Nettles, Ph.D.

**2.2.11.2 Description.** This task will develop, refine, and validate a method for locating and characterizing impact points in anisotropic structures. In 2014, parts of this effort were integrated with another SLS contract on the Advanced Booster with ATK.

The TM of this activity, Alan Nettles, Ph.D., worked with the principals to use data collected from ATK on impact testing of composite cases for SRMs. These data are being used to validate the algorithm and methodology.

## 2.3 Advanced Booster Engineering Development Risk Reduction Contracts

The SLS will provide an entirely new capability for human exploration beyond Earth orbit. Designed to be flexible for crew or cargo missions, the SLS will be a safe, affordable, and sustainable capability to continue America's journey of discovery from the unique vantage point of space.

The SLS ABEDRR activity intends to reduce risks leading to an affordable advanced booster that meets the evolved capability requirements of the SLS, and enable competition by mitigating targeted advanced booster risks to enhance affordability.

The ABEDRR contracts were selected and awarded in late 2012 and early 2013. Sections 2.3.1 through 2.3.4 have brief descriptions of the selected tasks, industry partners, and progress to date.

### 2.3.1 Dynetics and Aerojet

**2.3.1.1 Description.** Dynetics was originally awarded two major tasks. The first task was focused on modernization of the Saturn era F-1 engine, designated the F-1B, with an objective to reduce development cost and risks in critical areas. The second major task dealt with cryogenic tanks with the objective to reduce cost and risk by designing, manufacturing, and testing a cryogenic tank assembly.

Dynetics' subcontractor for the F-1B work was Pratt & Whitney Rocketdyne (PWR). Subsequent to the contract award, the Rocketdyne division was purchased from Pratt & Whitney by Aerojet who renamed the new entity Aerojet Rocketdyne. The heritage Aerojet company had an ABEDRR task to investigate combustion stability in a large-scale, oxygen-rich, staged combustion (ORSC) chamber. Following the formation of Aerojet Rocketdyne, the ORSC Combustion Stability task was consolidated under the Dynetics contract as a third task.

**2.3.1.2 F-1B Engine Task Description.** The objective of this task is to reduce cost associated with F-1B engine development and manufacture in three critical areas: (1) Gas generator (GG), (2) turbopump assembly (TPA), and (3) main combustion chamber (MCC). The F-1B design will incorporate lower cost component designs and improved materials compared to the heritage F-1. Modern and more affordable manufacturing processes will demonstrate a significant reduction in development time and production cost. Existing engine components will be updated with the new parts for testing to establish performance, throttling, and transient characteristics. The F-1B GG injector design will be produced using SLM low-cost manufacturing techniques (fig. 42) and then hot-fire tested.

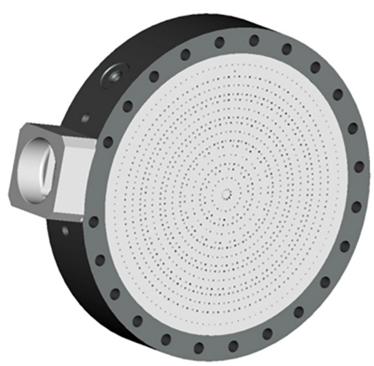


Figure 42. Dynetics ABEDRR SLM GG injector design.

A full-scale, modern thrust chamber assembly (TCA), consisting of the MCC and nozzle, will be designed leveraging advanced, lower cost, manufacturing methods such as channel wall nozzle (CWN) and hot isostatic press (HIP) bond (fig. 43). By contrast, the original F-1 used a nozzle fabricated using a brazed tubewall process that was very labor intensive. The modern manufacturing methods will significantly reduce part counts and time required to assemble.

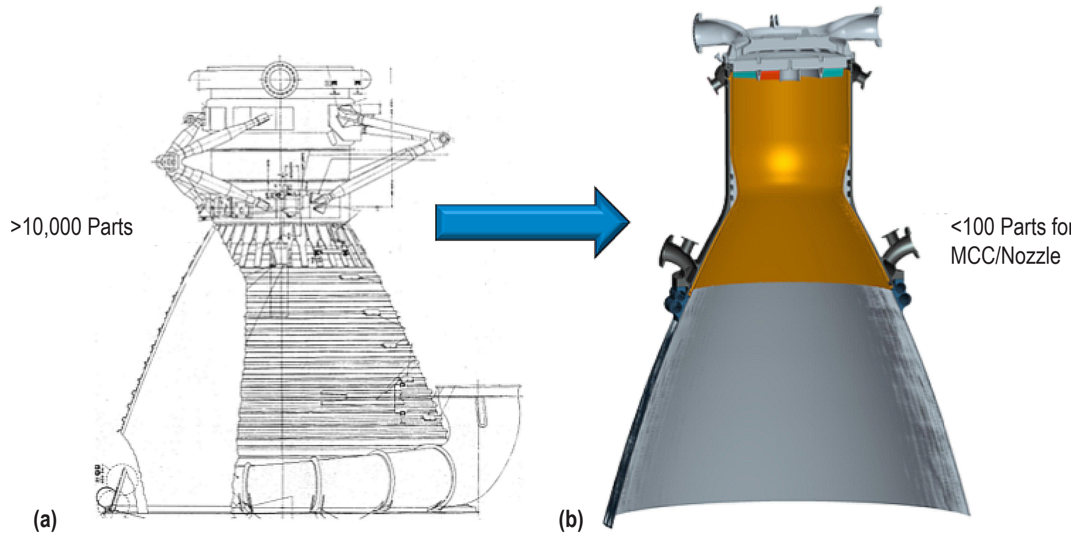



Figure 43. Dynetics ABEDRR F-1B MCC: (a) Tubewall TCA and (b) hot isostatic pressed MCC and CWN.

For turbomachinery manufacturing risk reduction, a new LOX pump volute, turbine manifold, and turbine blade castings will be manufactured with the objective to demonstrate the ability to reproduce full-scale F-1 hardware that have high cost and schedule risks to design, development, test, and evaluation (DDT&E).

**2.3.1.3 Combustion Stability Task Description.** Although successfully developed by the former Soviet Union, a LOX/rocket propellent (RP) ORSC engine has never been developed and flown by the United States. One of the largest risks in the development of this type of engine is combustion instability. The purpose of this task is to reduce the risk and improve technical maturity of fielding a LOX/RP ORSC booster.

Aerojet Rocketdyne's proposed AR-1 is a 500,000-lb-thrust, LOX/RP ORSC engine. This effort will build a full-scale main injector and TCA similar to what would be used on a future AR-1 or other ORSC type engine. The current effort will also build a test rig and prepare the assembly for future testing designed to measure performance and demonstrate combustion stability.

The USAF is also interested in LOX/RP ORSC technology. The USAF is conducting the Hydrocarbon Boost (HCB) program aimed at developing and demonstrating ORSC hardware and providing data to anchor physics-based models. NASA and Aerojet have partnered with the USAF to leverage use of HCB hardware in the ABEDRR test setup.

The Aerojet test configuration is comprised of two 250,000-lbf class preburners feeding a single 500,000-lbf class main injector and thrust chamber. The USAF will supply the preburners. The main injector, chamber, and overall test rig (fig. 44) will be designed and fabricated by Aerojet and their major subcontractor, Teledyne Brown Engineering. The test rig will be designed to interface with the E-1, cell-1 test stand at Stennis Space Center. By the end of the task, Aerojet will have completed fabrication of the test assembly.

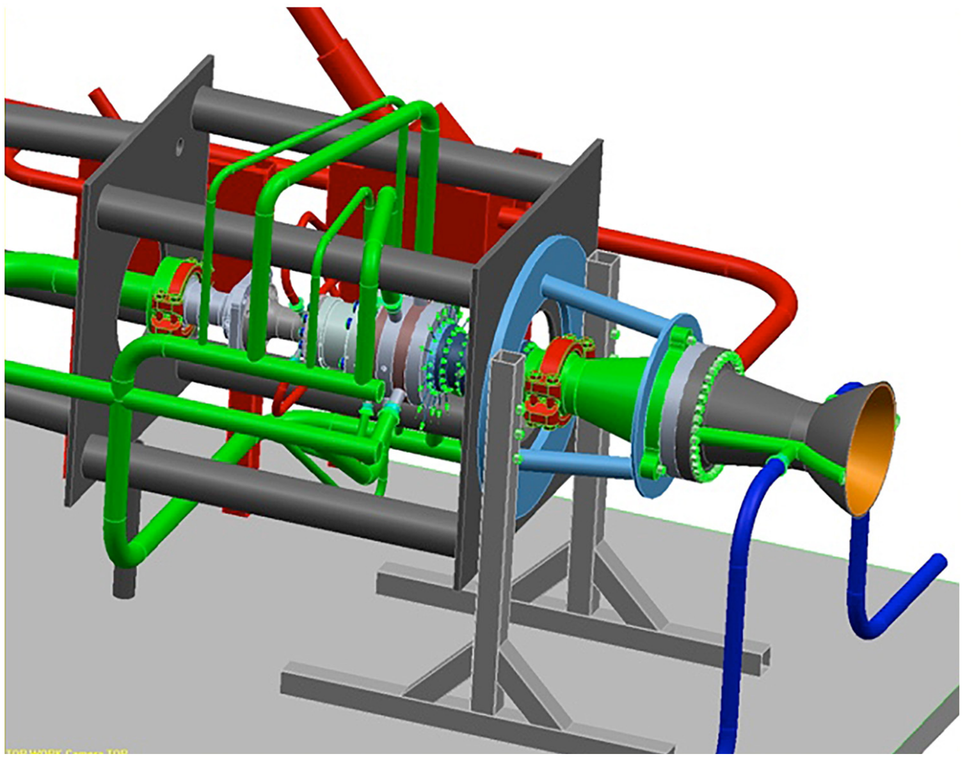


Figure 44. Aerojet ABEDRR full-scale combustion stability test rig.

**2.3.1.4 Structures Task Description.** The objective of this task is to reduce cost risk by designing, manufacturing, and testing a cryogenic tank assembly. In this task a prototype cryotank and intertank will be designed to leverage affordable manufacturing processes (fig. 45). A shortened cryotank will be built and tested to demonstrate the design and manufacturing tools and processes. The cryotank will be instrumented and installed in a vertical test stand for static proof pressure and cryothermal cycle testing.

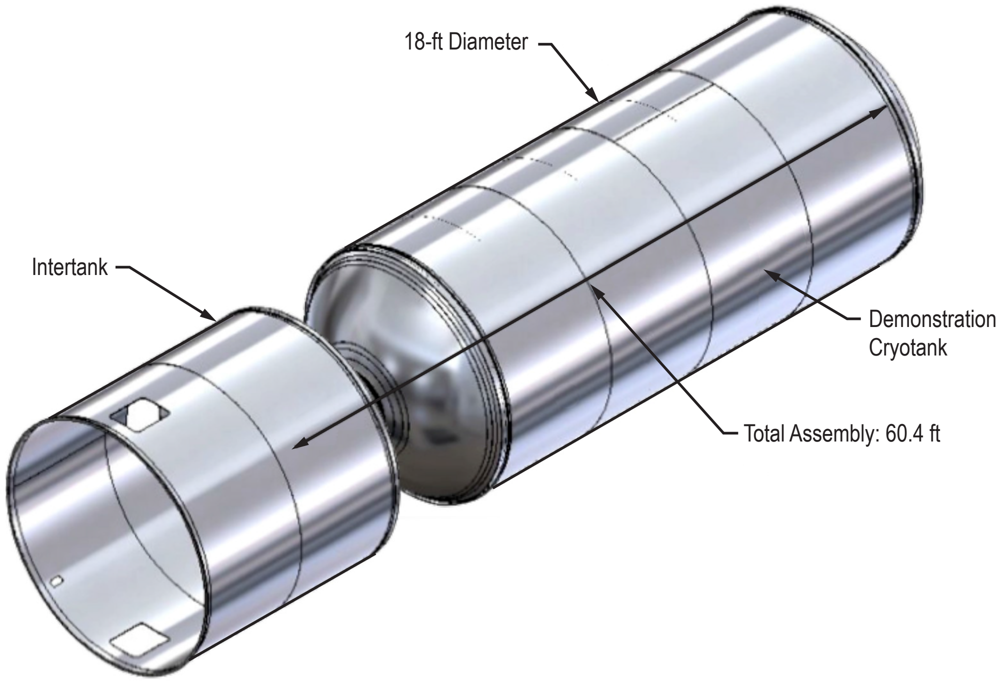



Figure 45. Dynetics ABEDRR cryotank/intertank assembly.

MSFC's FSW facilities and tooling in Buildings 4755 and 4707 will be utilized. The tanks were designed and built to validate low-cost materials and methods to produce booster structures for DDT&E. Thick-walled monocoque construction eliminates the cost and risk from machining large, complex grid panels and expensive T-ring forgings.

Common tank domes and one-piece barrels reduce parts count and improve reliability. The cryotank assembly build systematically addresses the risks associated with the design, materials, manufacturing, and NDE processes selected to produce structures. This task will also confirm that the manufacturing facilities and equipment at MSFC are suitable for building full-scale tanks and structures, validating DDT&E and production cost savings from utilizing these facilities.

**2.3.1.5 Accomplishments.** Accomplishments achieved for the F-1B engine, combustion stability demonstration, and structures tasks are given in sections 2.3.1.5.1 through 2.3.1.5.3.

2.3.1.5.1 F-1B Engine. Under this effort, in FY 2013, a heritage GG was successfully hot-fired at MSFC's test stand 116 (fig. 46). The test article was an F-1 GG assembly from F-1 engine F-6049, a flight spare from Apollo 12. The test series successfully demonstrated the operating characteristics of the GG injector and chamber hardware at F-1B nominal and throttle conditions. In FY 2014, a new GG injector was fabricated using SLM. The GG was designed to replicate the heritage GG but designed, and optimized, for SLM manufacturing processes. The GG was fabricated, proof tested, and delivered to MSFC for water flow testing (fig. 47). The GG will be hot-fire tested at MSFC's test stand 116 in FY 2015.

Figure 46. Dynetics ABEDRR GG testing at MSFC.

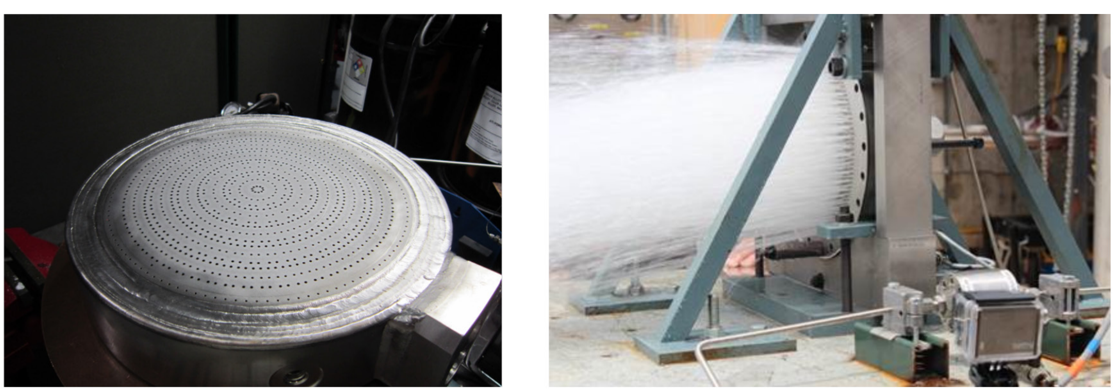


Figure 47. Dynetics ABEDRR SLM GG assembly and water flow testing at MSFC.

A heritage F-1A turbopump assembly (MK-10A) was disassembled and hardware inspections and analysis were conducted. A product definition of the 'as-built' hardware was developed using a technique called structured light scanning. The technique uses photos that are turned into high-fidelity 3D models that can then be compared to the existing engineering drawings. This approach was used for the LOX and fuel volutes, LOX and fuel inlets, LOX and fuel impellers, LOX and fuel inducers, turbine bearing support, turbine manifold, and first and second stage turbine blades. Using this technique, Aerojet Rocketdyne was able to develop a 3D assembly model of the actual as-built hardware for ≈1,000 hours less than creating a model from heritage drawings (fig. 48). The new models were used to perform a turbine gas path CFD analysis, an axial thrust analysis including force balance, and a rotordynamic analysis.

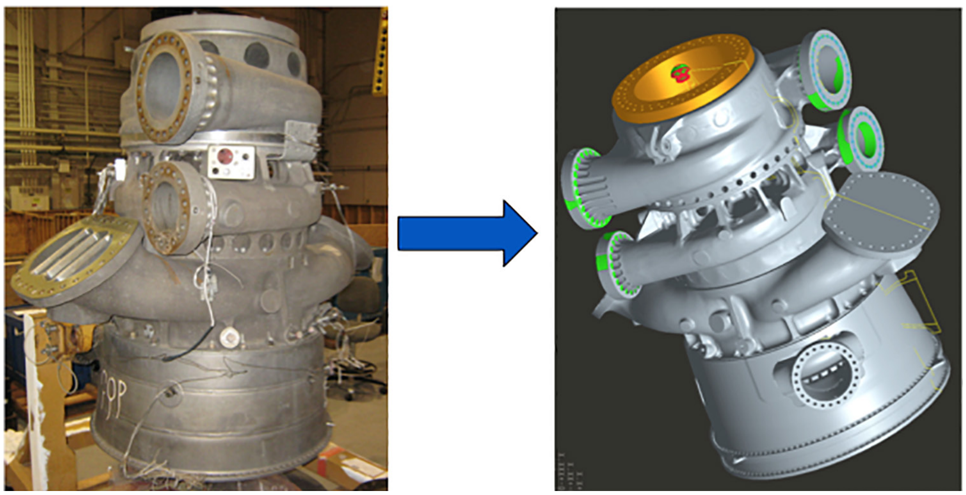


Figure 48. Three-dimensional model produced from SLS of heritage ML-10A turbopump.

The next phase of the turbomachinery risk reduction effort was to demonstrate successful manufacture of key components using modern casting techniques. Three aluminum sand castings were completed for the LOX volute. The first casting demonstrated a successful pour with complete fill, the second was sectioned to verify critical regions met drawing requirements, and the third was accepted as a deliverable product (fig. 49). The casting development demonstrated significant improvement compared to other programs which had required 10 castings. The lead time was reduced from 24 to 16 months. In addition to the LOX volute, turbine blades suitable for hot-fire testing and turbine manifold parts were also fabricated using the sand casting process.

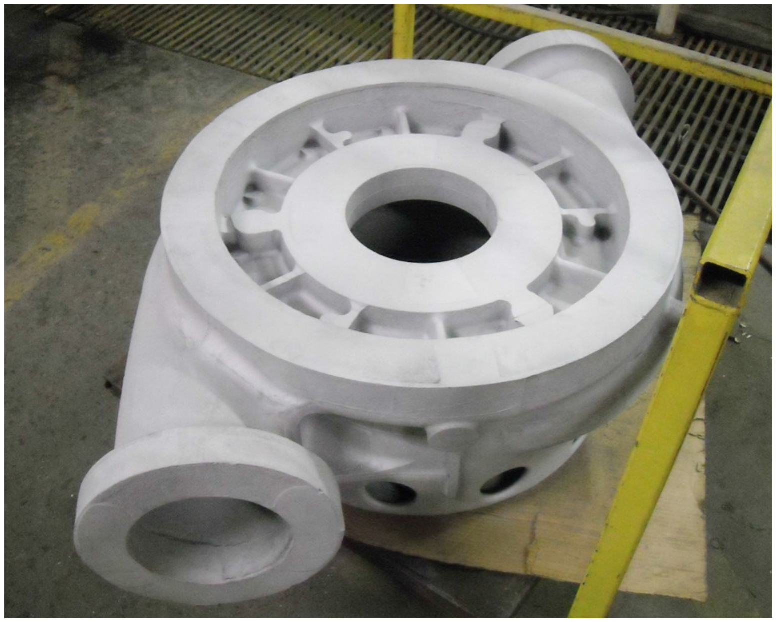


Figure 49. Dynetics ABEDRR turbopump activity: LOX volute sand casting.

The last major piece of the F-1B turbomachinery risk reduction effort was to demonstrate the design and build the TCA using a channel wall nozzle design and an HIP bonding process. Due to funding constraints, this task was reduced in scope before completion, but several milestones were reached. All major main combustion chamber components were drawn and ready for fabrication. Major tooling was ready for fabrication. Only final assembly drawings and minor tooling drawings remained. Structural analysis indicated the HIP cycle would result in acceptable bonding of the liner to the jacket.

2.3.1.5.2 Combustion Stability. The goal of this task is to build and test a full-scale ORSC engine main combustion chamber for the purpose of demonstrating combustion stability. In the past year, the NASA and Aerojet Rocketdyne team derived test article requirements and matured the test article design to a Preliminary Design Review (PDR) level. The injector is the heart of the engine and the effort began with five families of injector designs under consideration. Combustion stability of the engine as a whole is largely dependent on the design of the injectors themselves. The five candidate injector designs were evaluated through extensive use of CFD. Two of the five candidates were eliminated from further consideration prior to PDR and three candidates were taken to PDR.

The designs of other parts of the test article, including TCA and integrating components, were also matured during this time period. Test facility requirements were defined and designs developed to provide the high-pressure, high-volume propellant flows required for testing.

Following PDR, the selection of injector concepts and chamber design was further matured through CFD analyses validated by data obtained from the previous RS-84 unielement test program. Finite element analyses and other computer-aided design methods were utilized to reach low cycle fatigue goals, match the system power balance pressure budgets, and low- and high-frequency stability goals.

A shielded element injector design was selected as the primary candidate for the test article detailed design and manufacture following PDR. The team also selected Mondaloy™ as the primary structural material for critical parts exposed to the hot oxygen-rich flow environment required to test the main injector. Mondaloy is a superalloy that offers vastly superior strength and combustion resistance at the temperatures and pressures required for the test article and in oxygen-rich staged combustion engines. In addition to demonstrating combustion stability, the ABEDRR program provides the opportunity to demonstrate Mondaloy material suitability using cast, selective net shape, and forged parts. The material and manufacturing methods have direct applicability to future staged combustion hydrocarbon engines.

2.3.1.5.3 Structures. During FY 2014, extensive fabrication activities were conducted to validate the designs, materials, equipment, and processes to produce robust and affordable structures.

The fabrication activities started with a mill run of Al 2219 plate. The plates were delivered to Spincraft for spin-forming domes and to Major Tool and Machine for manufacturing of the tank and intertank barrels. A unique single-sheet barrel rolling technique was developed for the robust tank structure and demonstrated on seven barrels. These barrels were transported to MSFC for welding. ATI Ladish started with large aluminum ingots and worked them into ring forgings. The forgings were sent to Major Tool and Machine to be machined into y-rings.

Dynetics developed a tank build plan to weld the barrels using MSFC FSW tools. Weld schedules were developed on an MSFC Production Development System (PDS). First, the team developed 0.750-in conventional FSW parameters. These were successfully implemented on longitudinal barrel welds on the vertical weld tool (fig. 50). All barrels passed PAUT and dye penetrant testing. The original plan for start-to-finish time on welding operations and trimming barrels to length operations was 17 working days; Dynetics was able to complete the operations in 6 working days.

Figure 50. Dynetics barrels on MSFC's FSW tools, vertical weld tool (near) and vertical trim tool (far).

Following all the longitudinal welding, the weld schedule for 0.600-in SR-FSW was developed on the PDS and transferred to MSFC's robotic weld tool for circumferential welding of the two domes to the y-rings (fig. 51). Dome to y-ring welds were successfully completed, passing PAUT and dye penetrant testing.

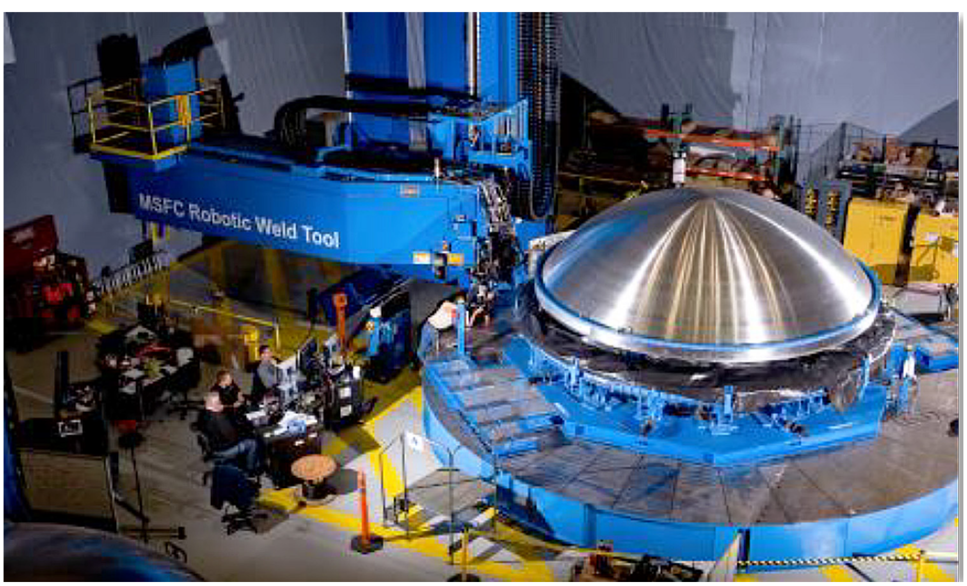



Figure 51. Tank dome on MSFC's robotic weld tool.

Finally, a weld schedule was developed for 0.750-in SR-FSW for circumferentially welding the tank barrels to the dome/y-ring assemblies and the barrels to other barrels on MSFC's vertical assembly tool (fig. 52). Mechanical modifications were made to the tool to accommodate the size and weight of Dynetics' structure. Top and bottom covers (manway and sump, respectively) will be added to complete assembly of the tank structure.

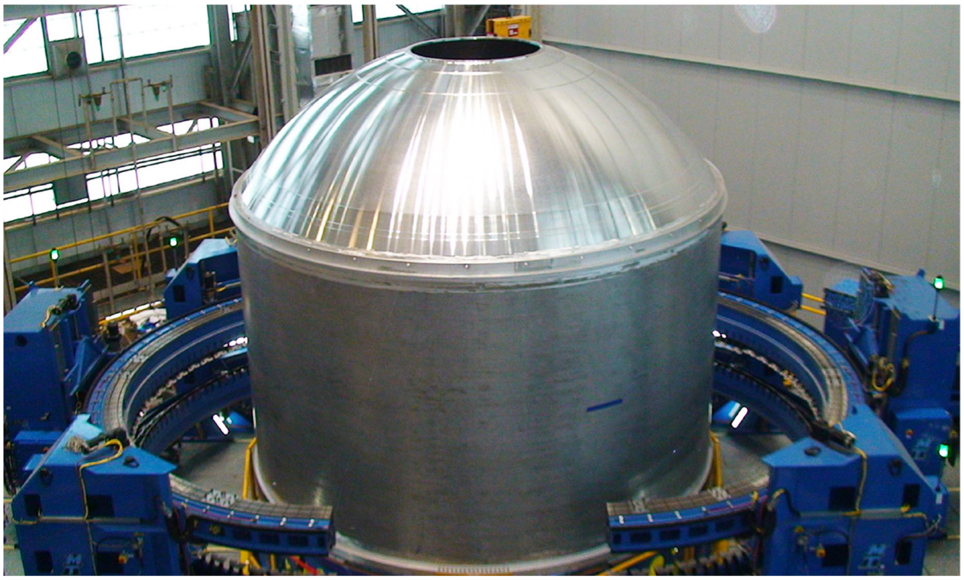


Figure 52. Near complete tank assembly on vertical assembly tool.

**2.3.1.6 Future Work.** Future work for Dynetics and Aerojet Rocketdyne involving the F-1B engine, combustion stability, and structures tasks is listed in sections 2.3.1.6.1 through 2.3.1.6.3.

2.3.1.6.1 F-1B Engine. The SLM manufactured GG will be tested at MSFC in the fall of 2014.

2.3.1.6.2 Combustion Stability. Combustion stability includes the following:

- The test article design will proceed to Critical Design Review in February 2015.
- The main combustion chamber will be fabricated in the summer of 2015.
- The injector and inlet diffuser will be fabricated in late 2015 and early 2016.
- Test stand modifications in preparation for testing will be performed in FY 2015 and early FY 2016 with test stand activation planned for the spring of 2016.
- Testing is planned for the summer of 2016.

2.3.1.6.3 Structures. Structure work includes the following:

- Complete preparation of the cryotank test stand at Iuka, MS.

- Conduct proof testing and cryo loading testing of the single-barrel tank test article in late winter of 2015.

### 2.3.2 ATK

**2.3.2.1 Description.** The goals of ATK ABEDRR activities are to benefit advanced booster development with improved performance, reliability, and affordability. The knowledge gained in the awarded tasks will advance the state of critical large booster systems and provide measurable data to assess a future advanced booster DDT&E competition.

One task is a static test article that is a 24-in diameter. It is an analog of the contractor's advanced booster concept. The tasks associated with the static test of the 24-in test article is the build, assembly, static test, and disassembly of a solid rocket booster (SRB) as an analog test bed for the contractor's advanced booster concept. Activities include composite case damage tolerance assessment, design and development, propellant development and characterization, nozzle design and affordability enhancement, and avionics and controls development.

The propellant, liner, and insulation task is geared towards developing a tailored thrust trace across a range of propellant family formulas that improve performance and mechanical properties while assessing a more producible booster at a more affordable cost. The goal is to gain an indepth understanding of propellant, liner, and insulation compatibilities.

A new nozzle flex bearing design will eliminate the need for the current flex boot and enable the use of a lower torque thrust vector control (TVC) system. This enables a lower weight and lower cost system that is significantly easier to process at the launch site.

The damage tolerance and detection task for a composite case is another enabling activity for ensuring the advanced booster case is safe for flight. This task is to gain an understanding of damage tolerant design solution effectiveness and give confidence to critics of composites.

**2.3.2.2 Accomplishments.** The following accomplishments were achieved:

- Propellant liner insulation (PLI)—Completed propellant design of experiment including tailoring of liner formulation, propellant testing, and analysis of 1 pint, 1 gallon, and 5 gallon mixes for four formulations; downselected to the HTPB formulation.

- Case damage tolerance—Completed manufacture of 92-in composite case and trial impact testing, including assessment of surface treatments, structural health monitoring, and nondestructive inspection options.

- Nozzle flex bearing—Completed design and drawing of assembly and primary components, including modification of tooling and manufacture of composite shims.

- Static fire test—Defined the 24-in motor static fire test configuration.

**2.3.2.3 Future Work.** Future activities for ATK are as follows:

- PLI—Perform 1,800-gallon mix, cast, and cure into 24-in motor. Demonstrate and assess the PLI system characterization.

- Case damage tolerance—Build, test, and assess burst case.

- Nozzle flex bearing—Build, test, and assess flex bearing. Perform kettle tests.

- Static fire test—Build, test, and assess 24-in static fire motor.

### 2.3.3 Northrop Grumman Aerospace Systems

**2.3.3.1 Description.** Northrop Grumman Aerospace Systems (NGAS) will conduct a subscale version of its common bulkhead composite tank set to demonstrate its SLS Advanced Booster concept. The contractor will deliver a final technical report summarizing the composite scale-up findings from the demonstration and test and include a comprehensive affordability plan.

The primary objective of this project is to design and test a composite demonstration subscale article that has been fabricated using out-of-autoclave (OOA) cure processes. The study will demonstrate the affordability, reliability, and performance benefits of the following composite tank set features: composite common bulkhead; an in situ OOA cure process; unitized tank shells with barrel, dome, and skirt; and an evacuated core sandwich construction.

The NGAS team will choose a composite tank set (CTS) scale that represents the engineering and manufacturing challenges for the objective system while minimizing development and test costs and providing best technical and cost value to the customer. The scale is expected to be approximately 8 feet in diameter and 32 feet in length, or about 50% of the objective system (fig. 53).

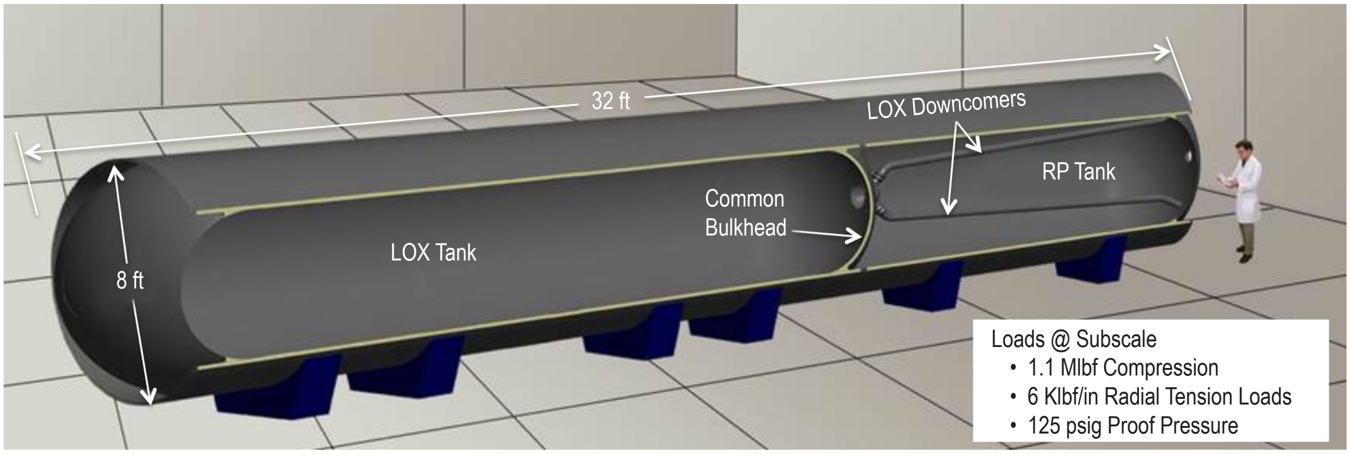



Figure 53. NGAS ABEDRR CTS demonstrator.

NGAS will collect affordability (time and materials, assembly methods and approaches, and supply chain and cost) and reliability data during the design, build, and demonstration test series, and correlate the results back to the NGAS affordability plan. By successfully conducting the CTS demonstration, this effort will show the potential for reducing or eliminating dome parasitic mass from natural path lamination, eliminating longitudinal joints with the production of unitized barrels, domes, and cones, and reducing facility costs and requirements with a single footprint facility approach. The overall effort also demonstrates the scalability of the in situ manufacturing and OOA cure processes to form the 8-foot-diameter CTS pathfinder to larger structures such as a 10-m shroud/fairing. The LOX composite tank during manufacturing and prior to removal from the mandrel is shown in figure 54.


Figure 54. LOX composite tank manufacturing.

The NGAS demonstration effort will provide cost, manufacturing hours, and reliability data regarding the benefits and drawbacks of a common bulkhead composite tank for a heavy-lift, SLS advanced booster, and other space exploration vehicle applications. Since existing American autoclave processing is limited to diameters less than ≈10 m and building new larger autoclaves is prohibitively expensive, the most significant challenge facing the NGAS team is the OOA curing of components of large unitized composite structures.

**2.3.3.2 Accomplishments.** Achievements include the following:

- Successfully built OOA test panels with <1% void content.
- Fabricated the test fixture and integrated the substitute fuel (diesel) supply tank.
- Designed and fabricated test fixture components and test sequence.
- Assessed and identified hazards associated with CTS testing.

**2.3.3.3 Future Work.** Future work of NGAS in FY 2015 includes the following:

- Perform mating and joining of all tank segments into a test article.
- Commission (baseline functionality, specifications, and safety) test stand at Griffin Aerospace in Madison, Alabama (fig. 55).
- Conduct tests.

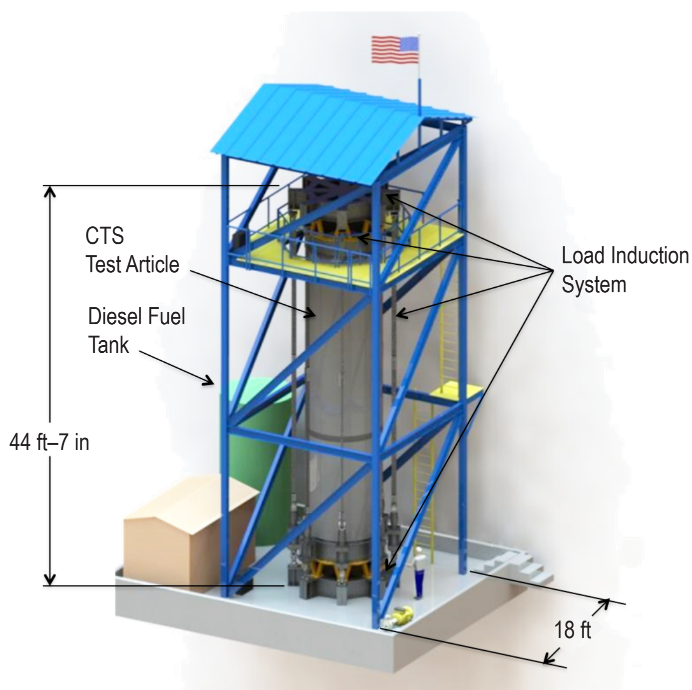



Figure 55. CTS demonstration test stand.

## 2.4 Industry Contracts

The Air Force's Advanced/Affordable Upper Stage Engine program (AUSEP) is an initiative to develop an affordable upper stage engine concept that will be a replacement for the RL10 engine. The AUSEP engine has the requirement for 30,000 lb of thrust with the performance of the RL10B-2 that can be packaged in the envelope of an RL10A-4 to support USAF evolved expendable launch vehicle (EELV) missions using existing Atlas and Delta launch vehicles.

AUSEP has additional goals for increased thrust and reduced size and weight for the SLS EUS to provide additional mission capture. The Human Spaceflight Architecture team analyzed the AUSEP requirements for crewed missions beyond Earth orbit.

The industry contracts were awarded in late 2012 and all were completed early in calendar year 2014. Contracts were awarded to five industrial partners. A brief description is provided in sections 2.4.1 through 2.4.5. An additional task was awarded to United Launch Alliance for an integrated vehicle fluids (IVF) task discussed in section 2.4.6. All but two tasks, Exquadrum and ULA/IVF, were completed in FY 2014.

### 2.4.1 Aerojet

**2.4.1.1 Description.** The Aerojet AUSEP team performed a system design study to derive the top-level system requirements and specifications for the overall AUSEP engine cycle using their next generation engine (NGE) system configuration as the emphasis. The work included a system engineering trade study focused on the affordability, performance, and technological maturity of their AUSEP NGE configuration.

The Aerojet study effort produced draft program plans, initial estimates of recurring and nonrecurring costs, and schedule necessary to design, develop, test, and manufacture a flight-certified engine system within a reduced cost and constrained schedule environment.

**2.4.1.2 Objectives and Scope.** Through the Aerojet team's assessment of their NGE in-house development as a viable replacement for the current RL10 upper stage engine, the team focused on three primary objective categories. The team worked to (1) establish the necessary engine performance requirements and verification, (2) provide a flight engine design supported by the appropriate analyses and trades, and (3) establish cost and schedule estimates for DDT&E of a suitable replacement flight engine system. The Aerojet AUSEP team met these study objectives by initially using their engine system functional analysis process to define the engine system requirements and allocate them to the major NGE subsystems and components. Using these engine system requirements, top-level DDT&E and manufacturing planning and initial cost and schedule assessments for engine production and integration were established and evaluated. Using a single design and analysis cycle, the study team refined the AUSEP engine system concept based on Aerojet's NGE-augmented expander cycle development work completed to date (fig. 56).

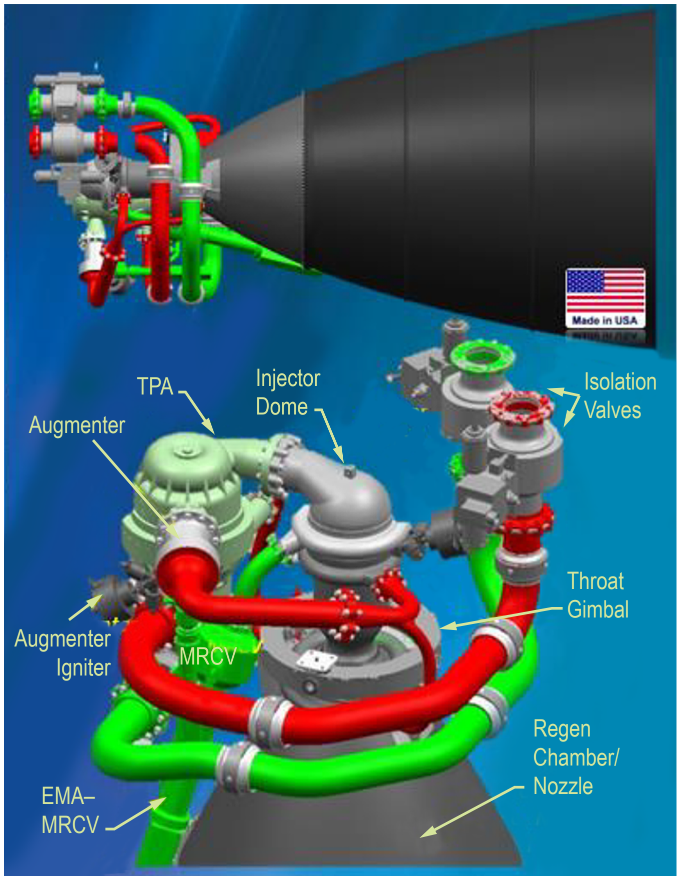



Figure 56. Aerojet AUSEP augmented expander cycle engine concept.

Additive manufacturing for the AUSEP NGE components was investigated as part of this study effort. A candidate set of AUSEP components were identified for evaluating the drivers associated with AM fabrication—specifically, direct metal laser sintering (DMLS). Each candidate component (initially designed for a typical machining method) was analyzed by applying the applicable AM material characterization data, structural optimization, and AM process optimization. To fully characterize the AM methods for each of the components, existing AM production data were used to verify the costs and production schedule for each.

The Aerojet team defined a set of appropriate FOMs to support the trade studies and analysis downselection process, with an increased emphasis on the cost and development schedule aspects of an AUSEP DDT&E concept. The team then performed cost and schedule estimates required to manufacture and produce their proposed engine system per their DDT&E program concept. The overall lifecycle estimate included a development, qualification, and production schedule, and recurring and nonrecurring costs. The overall study flow is shown in figure 57.

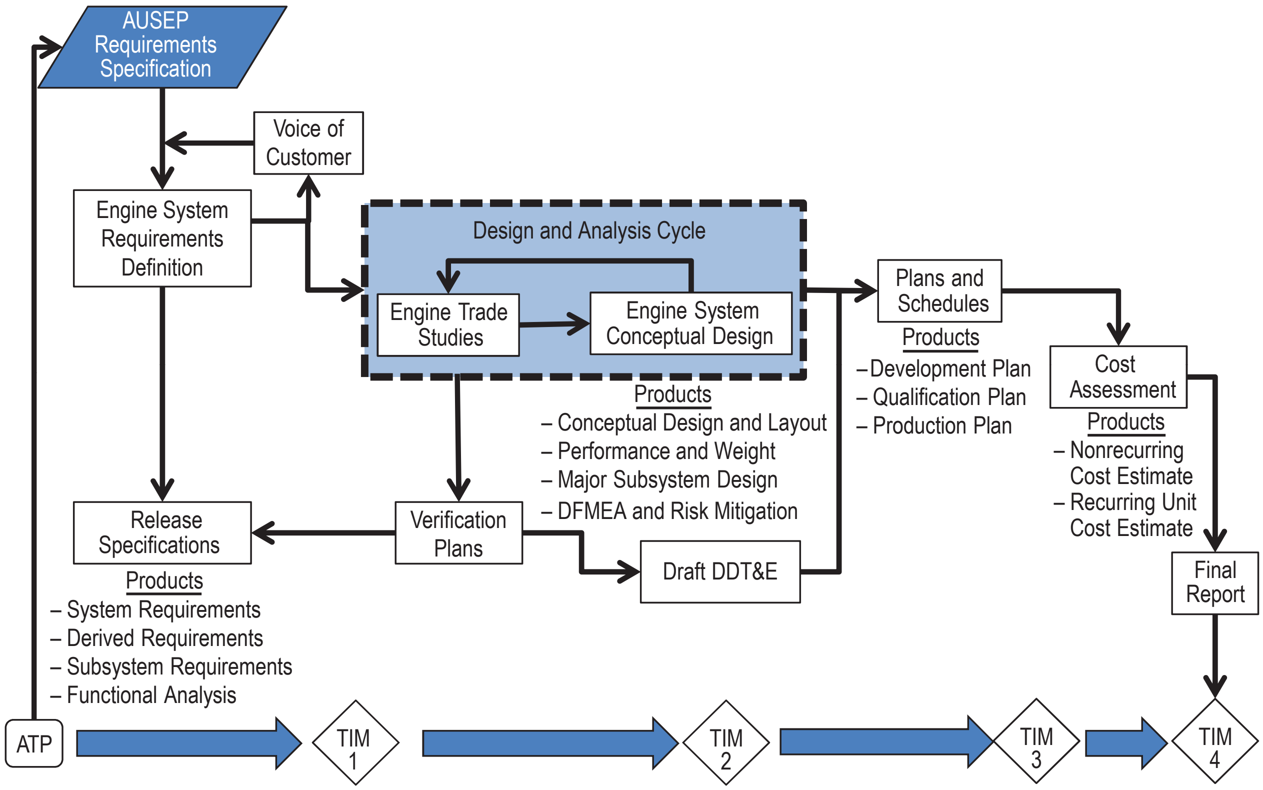



Figure 57. Aerojet AUSEP engine study flow.

**2.4.1.3 Accomplishments.** Aerojet accomplishments include the following:

- Developed the major subsystems requirements, associated verification requirements, and documents.
- Developed a series of power balance trades and analyses for the NGE AUSEP; nominal and off-design operation and for additional SLS mission capture.
- Defined a set of FOMs and weighted values reflecting increased importance of affordability aspects.
- Developed DDT&E cost and schedule estimates, including recurring and nonrecurring cost and schedule ground rules, assumptions, risks, and estimating methodology.
- Developed the flight engine production and delivery schedule.
- Delivered a finalized flight engine architectural layout with isolation valve models, bellows arrangements, and nozzle profile that align with the defined AUSEP performance requirements.

### 2.4.2 Exquadrum

**2.4.2.1 Description.** The Exquadrum team, along with teammates WASK Engineering and ATK, developed the dual-expander, short-length aerospike (DESLA) upper stage engine concept as an affordable replacement for the RL10 upper stage engine for the Air Force's EELV and that also meets the requirements for NASA's SLS program. The engine concept was developed using a design for manufacture and assembly approach. Key features of the DESLA engine include:

- Simplification due to reduction in hardware size, which enables TCA development to be performed at full-scale affordably.

- A modular TCA, which enables high volume production for a low volume engine.

- A dual expander cycle, which enables separate optimized turbopumps and eliminates the need for an interpropellant seal.

- Utilization of the AFRL's upper stage engine technology (USET) turbopump, which significantly reduces development technical and cost risk.

- A short aerospike nozzle, which provides the surface area and heat transfer necessary for the cycle without the need for a deployable nozzle extension.

Exquadrum's implementation of the modular thrust chamber is a key technology that enables the cost-efficient manufacturing approach that utilizes high volume module production for a low production volume engine. It replaces a single, large, expensive TCA that requires significant tooling, touch labor, and nonconformance disposition cost, with ≈200 small, inexpensive thrust chambers manufactured with conventional machines, minimal touch labor, and no nonconformance disposition cost. The size of the modular thrust chamber also enables emerging manufacturing processes, such as direct metal laser sintering and SLM processes.

In addition to the DESLA upper stage engine concept and requirements analysis study, a 60,000-lb thrust LOX/RP-1 engine conceptual design (fig. 58) was developed to size a modular thrust cell for a booster engine application. A detailed design of the RP-1 modular thrust cell was then generated for manufacture using the SLM process. Solid models, manufacturing drawings, and analyses documentation were provided to NASA for the manufacture and test of the thrust cell.

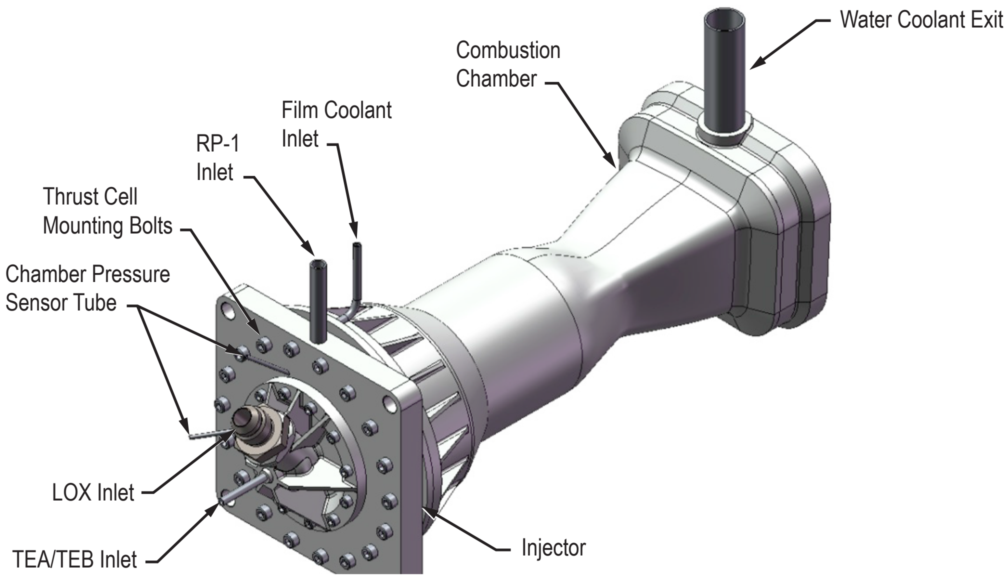



Figure 58. Modular aerospike engine LOX/RP-1 SLM thrust cell.

**2.4.2.2 Objectives and Scope.** The overall objectives of this effort were to perform trade studies in response to the USAF and NASA Upper Stage Engine program requirements, mature the resulting LOX/$LH_2$ engine configuration, generate recurring and nonrecurring cost, and schedule estimates to develop and produce the resulting engine configuration. Also, a conceptual design will be developed for a 60-Klb, LOX/RP-1 aerospike booster engine including a detailed design of a modular thrust cell suitable for manufacture using the SLM process.

To achieve these objectives, Exquadrum identified trade studies and subtasks in the following areas that focused on optimizing the DESLA design in response to the AUSEP requirements:

- Trade studies to optimize chamber pressure and nozzle area ratio have been identified to meet the maximum engine diameter requirement.

- Trade studies to evaluate nozzle configuration and length have been identified to meet engine performance and maximum length requirements.

These trade studies sought to identify an engine configuration that best met the AUSEP requirements. This configuration was modeled in the Rocket Engine Transient Simulator (ROCETS) application for steady-state and transient analysis to establish a high-fidelity engine power balance.

The resulting DESLA configuration was used to generate an engine conceptual design and used to evaluate packaging within the Centaur stage. Using 3D solid models of the engine design configuration, the engine system and component weights were calculated. The conceptual design was also used to generate a drawing package to support the analysis and estimation of manufacturing costs and schedule for an engine system development and certification program; first unit costs and recurring costs per engine system unit were also assessed. Additionally, using SLM development and processing approaches, a detailed design of a modular thrust cell was generated for manufacture.

The DESLA lifecycle cost and schedule estimates were developed; quantities and quality variables were used to bracket the analysis. Engine quantities were varied for development, certification, and production. Quality requirements spanned a continuum of commercial, USAF EELV, and NASA human-rated space flight requirements.

The results of this effort validated the DESLA engine's ability to meet the AUSEP requirements. The modular thrust chamber approach enables a high-volume production for a low-volume engine, which is critical toward lowering cost. The thrust cells can be manufactured affordably with conventional machining, no special tooling, minimum touch labor, and can take advantage of emerging SLM AM technologies. The aerospike nozzle area ratio is independent of nozzle length, which enables achieving performance requirements without excessive chamber pressure or engine length. The lower chamber pressure, and resulting engine system pressures, enables single-stage turbopumps operating at their optimum speeds. The dual-expander engine cycle eliminates the need for an interpropellant seal and lowers turbine inlet temperature due to the increased mass flow for low thermal gradients. Additionally, the AFRL USET $LH_2$ turbopump meets all DESLA requirements, which significantly reduces the engine development cost, schedule, and risk.

Significant progress was achieved during this study. Thousands of trade study runs were completed to identify the optimum engine configuration. Detailed thermal analyses of the regeneratively cooled nozzle and thrust chambers have been conducted using the ROCETS model. Pump hydrodynamic and turbine aerodynamic analyses have been conducted to generate pump and turbine maps for the fuel and oxidizer turbopumps for inclusion in the ROCETS model. The ROCETS model is being used to generate a high-fidelity power balance and to conduct transient analyses.

Incorporating the lessons learned from the AFRL test program, the conceptual design of the DESLA engine has been completed and a 3D solid model has been generated including a modified USET turbopump housing to reflect a flight-weight configuration; see figure 59. The engine weight has been calculated from the solid models, and verified to meet requirements. Turbopump general arrangement (fig. 60) and component manufacturing drawings have been generated and quality requirements identified to begin obtaining cost and schedule estimates.

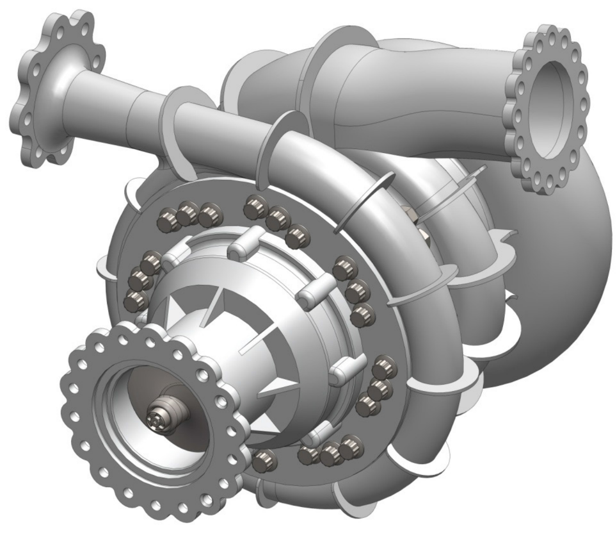


Figure 59. DESLA flight-weight TPA conceptual design.

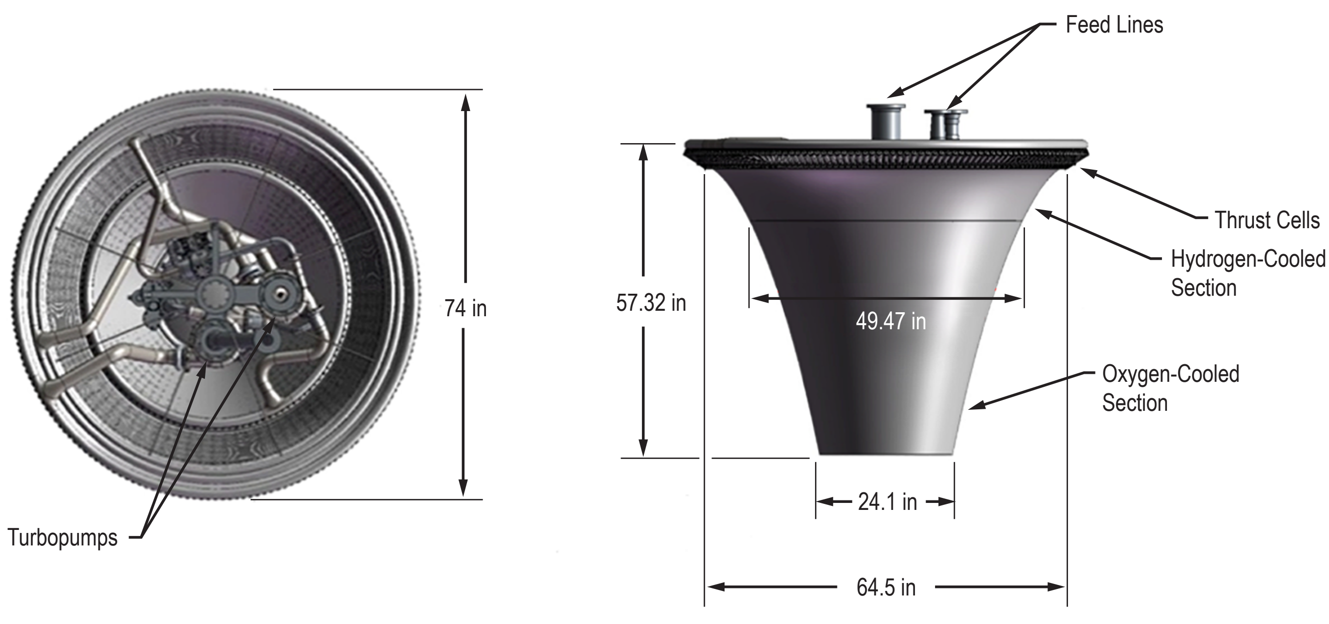



Figure 60. DESLA engine showing component placement.

**2.4.2.3 Accomplishments.** The following accomplishments were achieved:

- Initiated engine concept detailed trades and design studies; performed functional decomposition of AUSEP system requirements and developed a trade space definition document.

- Evaluated all planned cycles and created power balance models for all candidate architectures.

- Completed broad engine system trades involving alternate cycles, sizing studies, nozzle options, and turbopump configuration:
  – Selected and optimized the point of departure (POD) DESLA engine system concept specifically to meet the AUSEP requirements.
  – Performed thrust cell chamber and aerospike nozzle performance and area ratio trades and analyses (injector type, nozzle regenerative cooling circuit layouts, specific impulse (Isp), igniter, engine weight, and length).
  – Completed nozzle configuration trades and developed a regeneratively cooled channel geometry for the proposed aerospike nozzle.
  – Used the ROCETS code to model the resulting DESLA configuration to increase fidelity and provide transient analyses.

- Completed turbomachinery trades and analyses (number of stages, shaft configuration, bearing type and arrangement, material selection):
  – Completed turbine map modeling, analysis, and validation for the DESLA fuel and LOX turbines and the AFRL USET turbine; USET shown compliant with DESLA requirements.
  – Completed flight-weight designs of DESLA LOX and fuel TPAs based upon the USET turbopump design.

- Performed component level analyses and trade studies to finalize optimum configuration, including identification of potential technology insertion opportunities (with estimated benefits, costs, and risks identified).

- Using the external envelope of the defined DESLA engine, Exquadrum integrated the engine configuration into the Centaur upper stage model of the Atlas V, as provided by United Launch Alliance (ULA).

- Delivered draft Systems Engineering Management Plan (SEMP) for the DDT&E of the AUSEP configuration.

- Finalized the recurring and nonrecurring cost and schedule estimates for the DDT&E, and launch support, including total lifecycle cost, of an advanced upper stage engine.

- Produced a final technical report focused on NGAS closed expander engine conceptual design; included results of the trades and design studies conducted at the integrated engine level and at the component level to demonstrate compliance with the requirements of the trade space document.

### 2.4.3 Moog

**2.4.3.1 Description.** The Moog AUSEP team addressed the design, development, manufacture, and test of a high-pressure variable flow control valve suitable for cryogenic LOX propulsion systems and engines sized for cryogenic upper stage use. Moog's proposed scope and effort advances the technical maturity of a LOX flow control valve design concept that is applicable to the AUSEP. The Moog team initiated this design concept based on discussions with industry regarding potential AUSEP designs. Ultimately, the valve design was based on input requirements received from potential upper stage engine developers. The design is scalable to allow a single actuator/controller to be used as both the thrust control valve and mixture ratio control valve.

One key element in this effort involves the use of the SLM process to manufacture the main valve components from Inconel 718. This SLM process has shown the potential to greatly reduce the cost and lead time to produce complex parts from Inconel, and other materials; however, there is a need for more test data regarding the performance of Inconel 718 made with this process in a LOX environment, as compared to parts made from wrought Inconel. The SLM manufactured Inconel 718 valve is shown in figure 61.

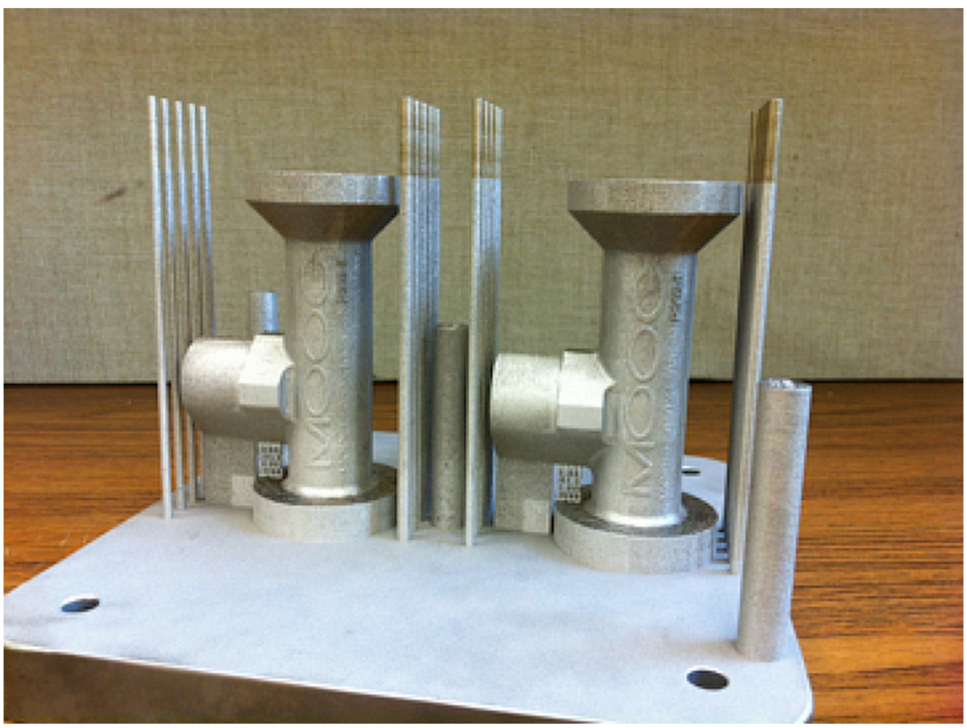



Figure 61. Moog AUSEP SLM LOX valve bodies produced at MSFC.

MSFC provided engineering, AM, and testing support per the direction of Moog for this program. This partnership with MSFC to provide test services allowed the demonstration of the valve assembly in the demanding high pressure and high flow LOX environment and provided for characterizing the valve with cryogenic nitrogen flow. The SLM manufactured Inconel 718 valve body, post-heat treatment, and material processing CT scan, HIP, heat treat, etc.) is shown in figure 62.


Figure 62. Moog AUSEP SLM Inconel 718 LOX valve post material processing.

**2.4.3.2 Objectives and Scope.** The primary objective of this development effort was to design and test a developmental valve to meet the derived flow and pressure requirements in both $LN_2$ and LOX flow environments (fig. 63).

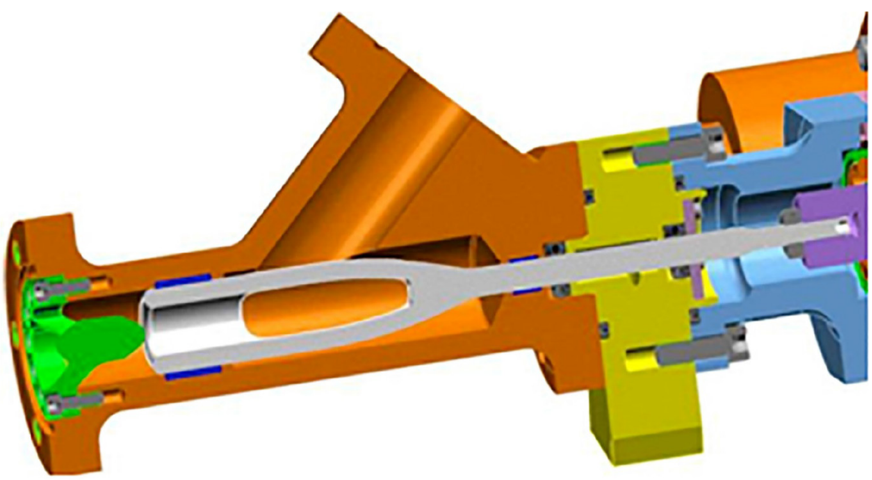


Figure 63. Moog AUSEP design concept high-pressure LOX control valve.

After deriving and evaluating the valve requirements per the engine supplier inputs, the team created a set of performance requirements. The valve design was iterated to allocate for the assessed performance requirements. To evaluate the valve's performance and adherence to requirements, acceptance and qualification test requirements were defined.

The developmental valve test program included two phases—component-level testing (i.e., certain key items will be tested separately) and full-scale valve testing. First, Moog measured and characterized the flow dynamics of the metering element by conducting water flow tests at Moog. This testing provided an early indication of flow versus pressure drop at multiple valve positions before progressing to the full-scale valve development, fabrication, and test phase. Second, the Moog characterized the dynamic seal performance in a cryogenic environment in order to quantify the friction characteristics of the seals at LOX temperatures and examine the tradeoffs between both seal leakage and seal life versus friction.

Moog followed parallel paths in the design of the valve body, using Monel K500 and Inconel 718. A Monel K500 body was produced using standard production methods. In parallel, Moog developed an Inconel 718 valve body; the valve was built by MSFC using an SLM advanced manufacturing process. Both valves were finished machined using traditional processes and tested with $LN_2$ and LOX. Both valves were built with a manual adjustment adapter, which allowed the valve to be placed at precise strokes and locked in place with a locking nut. $LN_2$ flow and pressure drop testing was performed on both the Monel and Inconel 718 valve bodies.

Through development and testing of the Inconel 718 valve body and its comparatively analysis to the Monel valve body, the Moog team met the objective of better understanding the applicability of AM for a cryogenic high-pressure valve design and to further assessing and advancing the overall quality and viability of AM methods.

**2.4.3.3 Accomplishments.** The following achievements were made:

- Completed the valve design effort to support the initial build of a development and test of a high-pressure cryogenic LOX flow control valve.

- Provided an initial understanding of the costs of producing a low-cost flight LOX valve and the potential cost savings areas associated with producing an AM cryogenic valve.

- Provided a final technical and management report discussing the design, development, test, findings, and future recommendations.

- Measured dynamic seal friction and dynamic leakage of the valve's critical dynamic seal.

- Conducted oxygen compatibility assessment of the Inconel 718 SLM valve and generated recommendations for a flight-weight valve design.

- Measured flow rate over a range of pressure conditions and valve positions.

### 2.4.4 Northrop Grumman Aerospace Systems

**2.4.4.1 Description.** Under an SLS NRA and in collaboration with the USAF, the SLS ADO awarded NGAS a contract for an upper stage liquid engine requirements study. With the closed expander RL10 currently being operated at 'red-line' levels, has multiple obsolescence items, and the RL10B production line nonfunctional for years, the NGAS AUSEP effort sought to perform a systems engineering trade study to identify an affordable, reliable, and technologically mature upper stage replacement engine configuration. The study effort produced draft program plans, including estimates of nonrecurring and recurring cost and schedules to design, develop, test, and manufacture a flight-certified system.

**2.4.4.2 Objectives and Scope.** The NGAS AUSEP study team initiated the design of a 30,000-lbf thrust class LOX/$LH_2$ affordable upper stage engine through an engine system requirements study phase. The study identified a cost-effective, technically mature alternatives to the often used RL10 engines. The study also identified modern design solutions that potentially make the replacement engine more affordable, consistent with performance and reliability objectives. The NGAS study team provided a conceptual engine design responsive to the upper stage engine system requirements, approaches, and systems engineering strategies applicable to full-scale engine replacement.

NGAS led an overall assessment and system configuration trades for a LOX/$LH_2$ advanced upper stage engine to select a liquid rocket engine concept for more detailed design trades. The team implemented affordability strategies in the design trades and approaches. A conceptual design of a baseline flight engine was then generated to establish operating characteristics and component requirements and interfaces, as well as to identify technical challenges and program risks. This engine concept was selected as the technical baseline to develop schedule and cost estimates.

Plans and strategies for the full-scale engine program were also generated to describe the analytical, design, development, testing, and hardware production methods and capabilities that support quantification of nonrecurring engine development and certification, and recurring production cost and schedule estimates.

A POD design (fig. 64) for an advanced engine compatible with the trade space requirements served as a starting point for more detailed studies and as a method to invite innovative thinking by encouraging the team to generate and consider multiple approaches and solutions. The engine POD design, developed during the proposal phase, is a closed expander thermodymanic cycle featuring a tank head start, and series driven turbines to achieve a simple, robust design with significant cycle power balance margin.

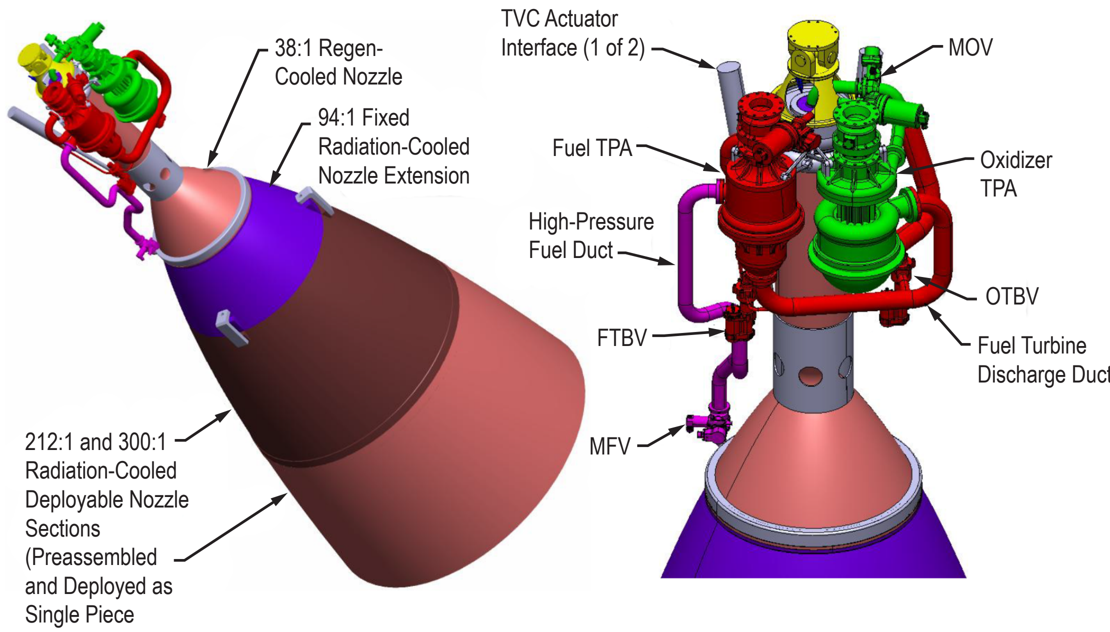



Figure 64. NGAS AUSEP POD closed expander engine layout and listing of components.

Based on the government-provided AUSEP requirements definition, information on engines of similar design, applicable findings from prior and ongoing programs, and NGAS-funded upper stage studies, the team conducted engine system trades and sizing studies for selection of the engine cycle, evaluation of the nozzle options, and initial assessment of the fuel turbopump configuration. Once these broad engine trades and sizing studies were completed, the focus turned to component-level trades and design studies in support of the POD engine design. With affordability being the organizing principle of this effort, detailed trades and design analysis cycles were conducted to assess whether the defined performance and reliability requirements could be achieved with simpler, modern solutions, thus deriving lower development, production, and operating costs.

**2.4.4.3 Accomplishments.** NGAS FY 2014 achievements include the following:

- Initiated engine concept detailed trades and design studies; performed functional decomposition of AUSEP system requirements and trade space definition document.

- Completed broad engine system trades involving alternate cycles, sizing studies, nozzle options, and turbopump configuration:
  - Selected and refined the POD closed expander engine system concept.
  - Performed thrust chamber trades and analyses (injector type, regenerative cooling circuit layout, nozzle cooling, igniter).

- Finalized detailed trades culminating in a closed expander engine concept design. Performance analysis results were evaluated and documented in the NGAS AUSEP final to the USAF and NASA.

- Completed turbomachinery trades and analyses (number of stages, shaft configuration, bearing type and arrangement, material selection).

- Finalized the recurring and nonrecurring cost and schedule estimates for the DDT&E of an advanced upper stage engine.

- Produced a final technical report focused on NGAS closed expander engine conceptual design, including results of the trades and design studies conducted at the integrated engine level and at the component level to demonstrate compliance with the requirements of the trade space document.

- Completed nozzle analyses and trade studies to finalize optimum configuration (deployable designs, candidate materials, joint to cooled chamber, etc.).

- Finalize and deliver the recurring and nonrecurring cost and schedule estimates for the DDT&E of an advanced upper stage engine.

### 2.4.5 Pratt & Whitney Rocketdyne

**2.4.5.1 Description.** The PWR AUSEP team performed a systems engineering trade study to identify an affordable, reliable, and technologically mature engine configuration for the EELV and then assessed its application to the NASA SLS Block 1a EUS. The results of their two-phase system trade study to identify an alternative to the RL10 engine for EELV and SLS vehicles that provides 30K-lbf thrust with a minimum Isp of 464 s were provided to the Government. The study also evaluated NASA SLS mission capture with a 35K-lbf thrust AUSEP derivative. The PWR study produced draft program plans, including rough estimates of nonrecurring and recurring costs and schedules to design, develop, test, and manufacture a flight-certified system.

**2.4.5.2 Objectives and Scope.** The study sought to balance affordability, reliability, and performance through the use of a proven utility analysis process, the process that employed interviews with the stakeholders (i.e., USAF and NASA) to derive a qualitative relationship describing the customer's utility preferences for a modernized advanced upper stage engine. The study concluded that the aggressive Isp and size requirements increase the complexity of the propulsion system, thereby limiting affordability-based utility to the stakeholders. Relaxing the Isp requirement potentially opens the trade space to options that are more affordable.

In the first phase, numerous configurations within the six cycles illustrated in figure 65 were surveyed at a system level to identify viable candidates for further study. Performance trades were conducted using PWR's well-established cycle prediction methodology. Physics-based power balance models were used to provide the rapid, accurate estimation of design and off-design characteristics using historically validated routines to predict the performance of pumps, turbines, nozzles, and other engine components. The engine configurations were ranked using the utility function characterized by customer preferences of affordability, weight, envelop, Isp, and reliability, with affordability ranking as the primary driver.

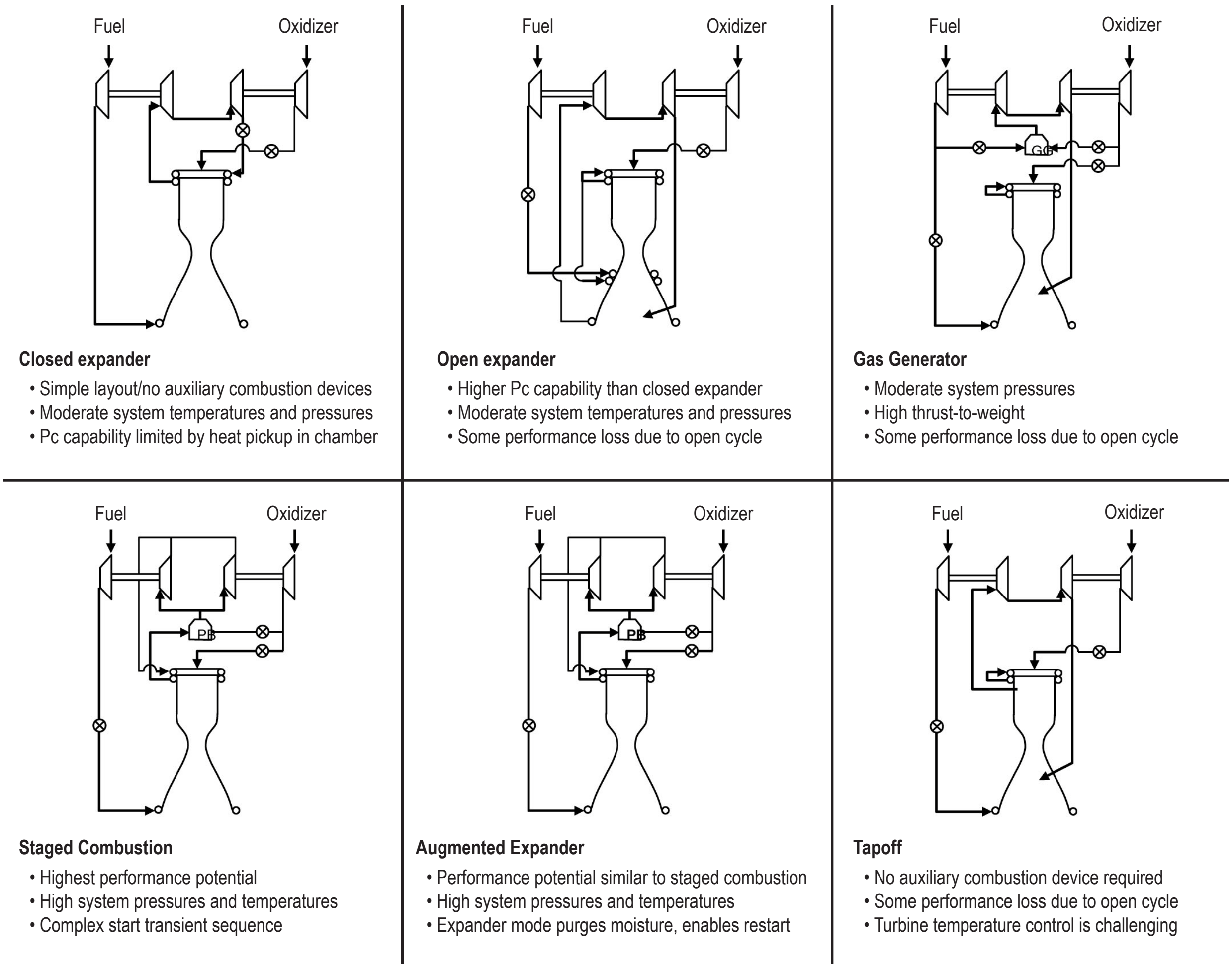



Figure 65. PWR AUSEP engine cycle trades.

When ranked for utility, most of the engine concepts examined provided minimal overall utility to the customer. Of the engine concepts evaluated, three architectures—dual chamber closed and open expander and augmented expander (AE) (a staged combustion/expander hybrid) engines provided the most customer utility. Dual chamber options facilitated potential affordability improvements offered by AM technologies. Taking advantage of technical maturity and potential AM affordability, the evolutionary RLXX was substituted for the closed expander configuration.

In the second phase, the three concept engines were examined in greater detail. Engine layouts were constructed using demonstrated component architectures available from previous advanced development programs. System weights were then estimated. The performance capability of individual components was examined based upon state-of-the art capabilities and possible innovations. System performance predictions were then updated to reflect the new component capabilities. Cost estimates for DDT&E (nonrecurring) and recurring production were derived using cost history of representative collaborative development programs.

The PWR AUSEP team's analysis determined that the augmented expander was the only concept meeting all customer requirements; however, it had a low utility score because of the high DDT&E costs. The customer utility of the dual chamber open expander engine was poor due to a combination of high weight, low system performance, and moderate DDT&E cost. PWR's analysis show that the technical mature, evolutionary closed expander RLXX utility is significantly better than the AE cycle even when unable to meet the Isp requirement.

**2.4.5.3 Accomplishments.** The following achievements were made:

- Evaluated all planned cycles and created power balance models for all candidate architectures.

- Developed a high-fidelity utility function balancing the main trade factors for affordability, weight, envelop, Isp, and reliability, based upon the USAF and NASA customer interviews.

- Delivered draft SEMP for the DDT&E of the AUSEP configuration.

- Finalized recurring and nonrecurring cost estimates for the three candidate engine cycle configurations from the rocket engine cost model.

- Performed component-level analyses and trade studies to finalize optimum configuration, including identification of potential technology insertion opportunities (with estimated benefits, costs, and risks identified).

- Finalized all draft program plans.

- Completed validation plan and established the potential development program schedules.

- Produced a final technical report focused on PWR three downselected engine configuration concepts, including results of the trade and design studies conducted at the integrated engine level and at the component level to demonstrate compliance with the requirements of the trade space document.

### 2.4.6 United Launch Alliance

**2.4.6.1 Description.** United Launch Alliance was awarded a task to extend their ongoing work for a system called integrated vehicle fluids (IVF). IVF increases upper stage performance by multiple tons and cuts unit costs by millions of dollars compared to traditional systems. IVF does this by eliminating all onboard helium, hypergolic propellants, large batteries, and multiple single-purpose valves; see figures 66 and 67. It supplies all power, attitude control, tank pressurization, and venting using two identical modules located 180 deg apart on the aft section of the upper stage. Each module contains a small internal combustion engine (ICE) which drives two low-pressure compressors, electrical generators, and gimbaled thrusters. The system runs off of the plentiful waste hydrogen and oxygen boiloff on cryogenic upper stages.

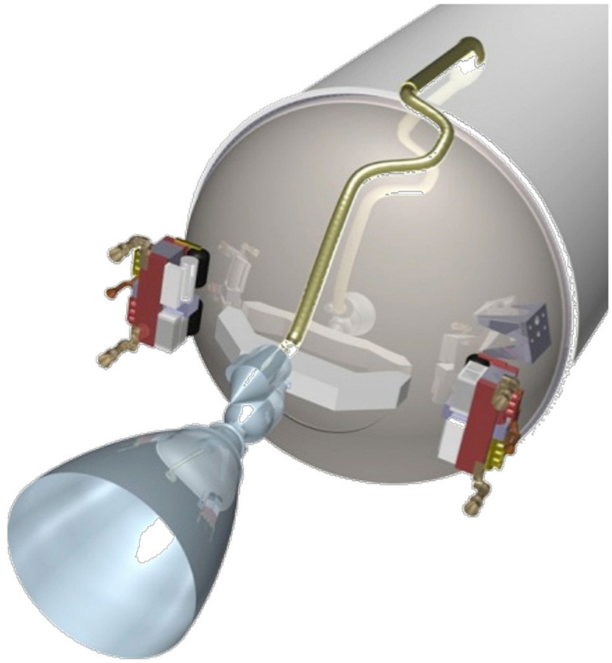


Figure 66.  IVF concept.

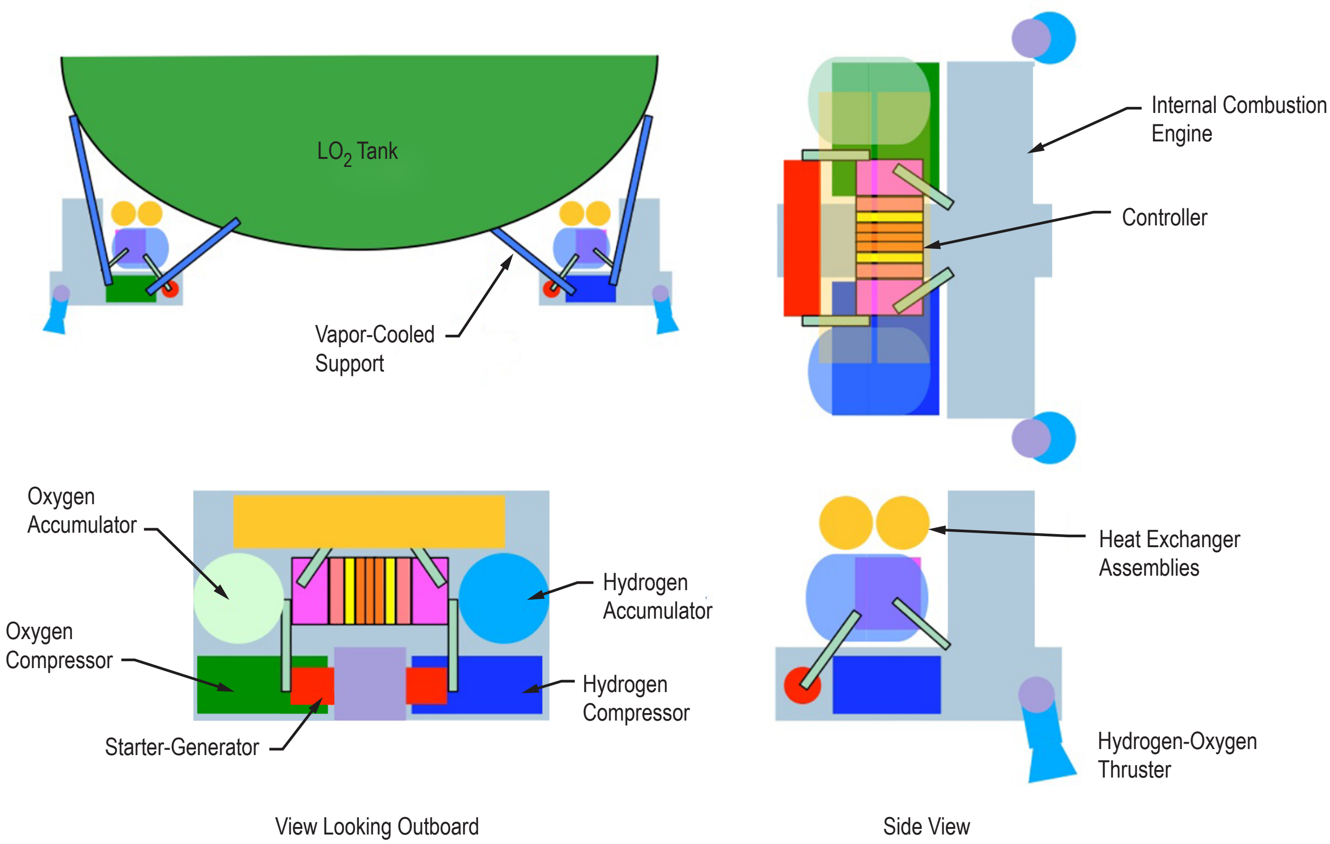



Figure 67.  IVF installation schematic.

**2.4.6.2 Objectives and Scope.** The objective of this task was to extend ongoing work performed in prior years by ULA to demonstrate greater system-level operation of IVF hardware. Prior work had shown reliable operation of the ICE and its associated valves as well as the hydrogen-burning thruster. However, key elements such as the cryogenic compressor, heat exchangers, cryogenic valves, high-voltage battery, electronic controller, and most especially, the interaction of these devices as a system had not been fully demonstrated.

This task focused on extended testing of the first generation system and demonstrated interaction of the starter/generator and high-voltage battery and ICE. Further system-level testing would be conducted on a follow-on Generation (Gen) 1.5 system which would incorporate all elements required to show cryogenic tank pressurization—the most demanding IVF activity.

**2.4.6.3 Accomplishments.** The Gen 1 system demonstrated stable operation of the ICE throughout the range of power levels. The interaction of the starter-generator and high-voltage battery was also demonstrated up to the capacity of the load banks. This testing identified no significant problems. In parallel, extensive testing of the proposed Krytox® lubricant was performed at bench level. Multiple metals and lubricant grades were tested. Krytox XP1A4 was selected as the lube due to its properties and wear results. The piston and cylinder materials and coatings for the Gen 1.5 ICE were selected based on this testing. In the end, 180 hours of run time were accumulated on the Gen 1 assembly before it was retired and subject to detail teardown inspection.

The project next built a follow-on Gen 1.5 ICE, cryogenic compressor, and a full complement of heat exchangers which are combined with Gen 1 generator, battery, and control electronics. The ICE incorporated flight-worthy Krytox lubricants and coolants. The Gen 1.5 integrated system is now under test through the end of the 2014 calendar year. Tests of increasing complexity and hazard are planned culminating in operation of the system using both liquid and gaseous hydrogen and oxygen. The complement of hardware in place will effectively demonstrate the system-level function of the IVF system.

In parallel, the first generation of the IVF controller was designed and manufactured. Lack of resources prevented the interfacing of this controller to the Gen 1.5 hardware but key firmware programming was completed to permit control of the primary ICE controls.

A substantial improvement in the IVF test facility was also made to enable high-flow testing with cryogenic hydrogen and oxygen. Systems for measuring IVF gas output as well as for circulating Krytox lubricant and coolant were emplaced and tested.

**2.4.6.4 Future Work.** With the completion of the 2014 test series, the flight design of IVF can commence in 2015. The focus of this follow-on work is the flight-weight design of the ICE and compressors and the integration of all valves, heat exchangers, controller starter/generator into a complete, compact package. The interfacing of the Gen 1 controller to the ICE and further development of this controller and its software to enable it to fully control IVF is a high-priority task.

# 3. SPACE LAUNCH SYSTEM EVOLUTION PATH

The SLS program approach to achieving an evolvable architecture has been to focus on the SLS Block 1 configuration (referred to as the inner loop design analysis cycle) and assess the SLS evolvability path by establishing an outer loop design analysis cycle (OLDAC) capability. The outer loop analysis runs parallel with the inner loop and thus is assessed at each major milestone review by the SLS chief engineer. This summary represents the evolved architecture feasibility developed by the OLDAC to meet program requirements for placing 105 and 130 t into low-Earth orbit (LEO).

## 3.1 Objectives

The objective of the SLS Evolvability (or OLDAC) team is to define, evaluate, and maintain cost, schedule, and technical characteristics of evolution paths from the SLS Block 1 system. The primary performance driver beyond Block 1 is to increase (or evolve) payload delivery from 70 t in LEO to 105 and 130 t, thus fully enabling a national exploration capability. To meet the objective of evaluating how well these evolutionary paths correlated with the NASA mission and with mission capture intent, additional research and analyses was performed for various mission destinations. These mission destinations include those defined in Exploration Systems Development (ESD) Concept of Operation and various other Human and Science Exploration Class missions. Assessments performed by the team are full lifecycle in scope, considering both technical and programmatic impacts of future vehicle upgrade decisions. These assessments also include impacts to the current Block 1 vehicle baseline to accomplish a particular path. Starting with the current Block 1 vehicle, a benchmark was performed to calibrate the analytical analysis approach and resulting performance predictions. From the benchmark, potential vehicle evolvability paths were defined, performance and cost evaluated, along with impact to the baseline Block 1 vehicle design established. The results of this comparison provide a basis for potential recommended changes to the Block 1 SLS in order to effectively accommodate a preferred evolution beyond SLS Block 1. This systematic approach, focused on launch vehicle capability and mission capture, allows the trade space to iteratively converge on an optimized solution that considers a full complement of both technical and programmatic factors.

## 3.2 Preferred Space Launch System Block Configuration Evolution Paths

To achieve the performance necessary to deliver 130-t payloads to LEO in support of future human lunar, Mars, and outer-planet missions, the Block 1 SLS will require additional performance in the form of developing advanced boosters and a new, high-performing upper stage. Figure 68 shows two primary paths to achieving these goals: Path A is centered on a J-2X-powered, 8.4-m upper stage combined with an RL10-powered, 5-m cryogenic propellant stage (CPS) and path B is centered on an RL10-powered, 8.4-m EUS. Prior to SLS PDR in the summer of 2013, path A evolved based on the assumption of developing the advanced booster first, followed by two upper

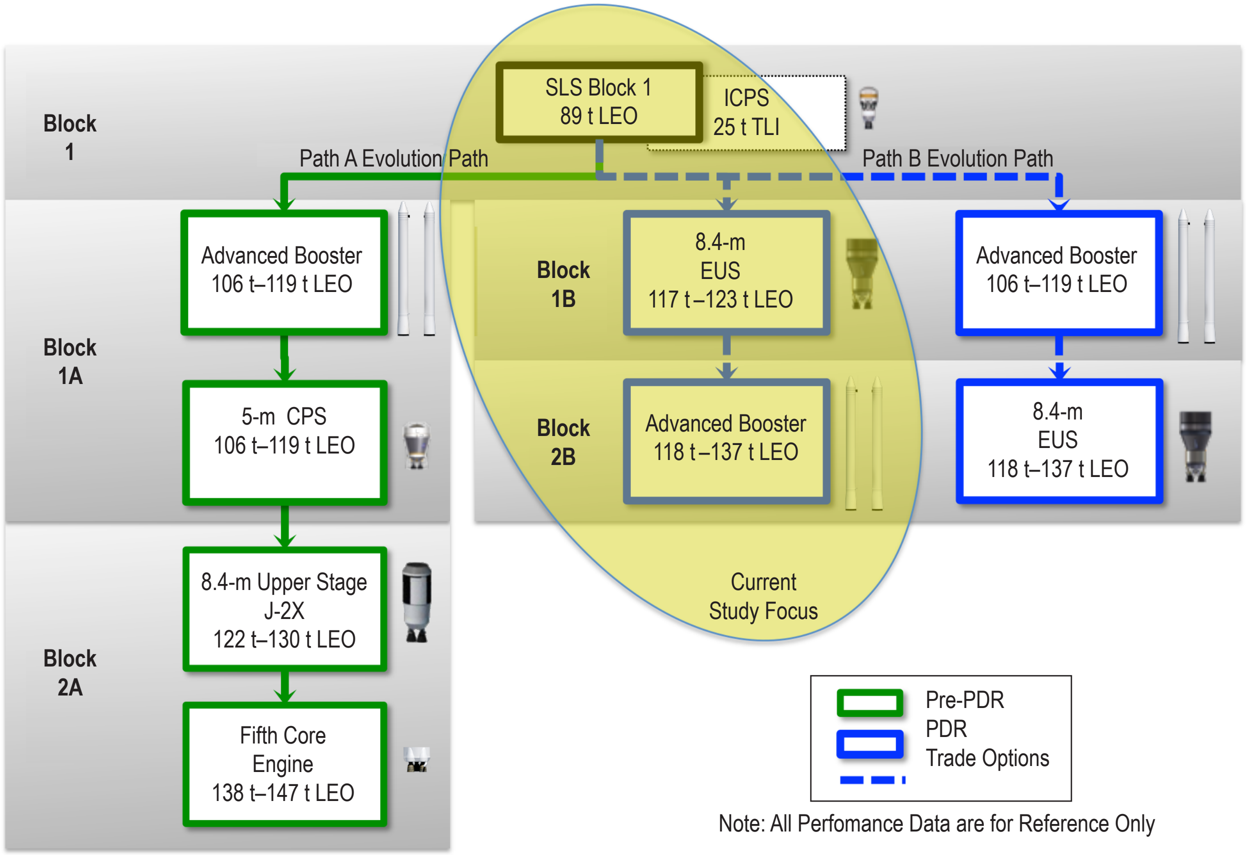
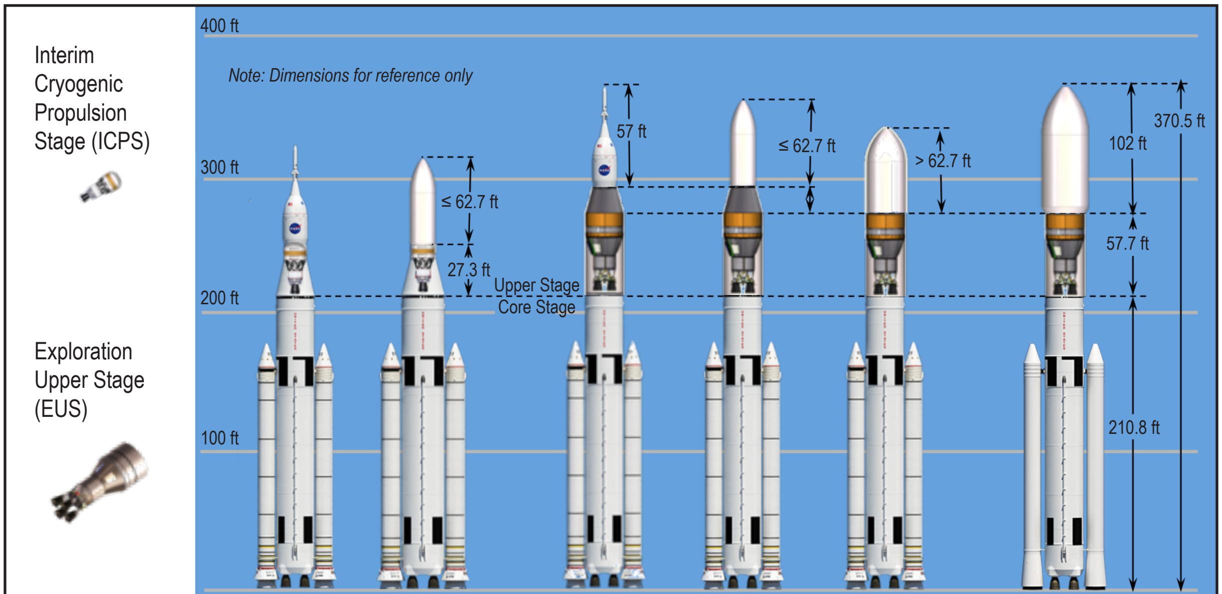



Figure 68. Possible SLS post-Block 1 evolution paths

stage(s) that would perform separate ascent and in-space transportation functions for the payload. When combined with the option of adding a fifth core stage engine, evolving to a path A post-Block 1, SLS could include development of as many as four new elements. Path B is centered on a single upper stage that provides a dual transportation function (ascent/in-space). In combination with the advanced booster, this reduced path B new element developments to two while providing a similar order of magnitude LEO mass delivery capability as path A.

Because of this, path B has been the focus of post-Block 1 evolvability studies over the last 12 months. Current SLS Block 1B development planning assumes availability for cargo missions using a 5-m fairing as early as 2021 (contingent on NASA priorities and budgets). Block 2B availability could be in the late 2020s (contingent on NASA priorities and budgets). The SLS Block 1 crew configuration (with the Orion multipurpose crew vehicle (MPCV)) is considered part of the SLS program baseline, while the SLS Block 1 cargo configuration (with 5-m fairing), Block 1B crew/cargo configurations, and Block 2B cargo configurations are considered SLS evolvability POD concept configurations. Figure 69 provides an overview of current SLS POD evolution configurations in comparison to the SLS program baseline Block 1 crewed configuration. These PODs are provided for reference only in order to provide a limited summary of path B configuration performance.




| | | | | | | |
|---|---|---|---|---|---|---|
| SLS Configuration | Block 1<br>(89 t LEO) | | Block 1B<br>(117 t IMLEO)<br>(93 t LEO) | | | Block 2 B<br>(138/140/152t IMLEO)<br>(119/120/137t LEO) |
| Vehicle ID | 10003 | 10500 | 28000 | 27500 | 27000 | 25000A/26000A/26001A |
| Core | 8.4-Common Core<br>4 RS–25D | | 8.4-Common Core<br>4 RS–25E | | | 8.4-Common Core<br>4 RS–25E |
| Booster | 5-Segment Shuttle Booster<br>RSRMV | | 5-Segment Shuttle Booster<br>RSRMV | | | Advanced Booster<br>ASB/GG/ORSC |
| Upper Stage | ICPS<br>1 RL-10B2 | | EUS<br>4 RL-10C2 | | | EUS<br>4 RL-10C2 |
| Payload | Orion | 5-m Payload | Orion | 5-m Payload | 8.4-m Payload | 10-m Payload |

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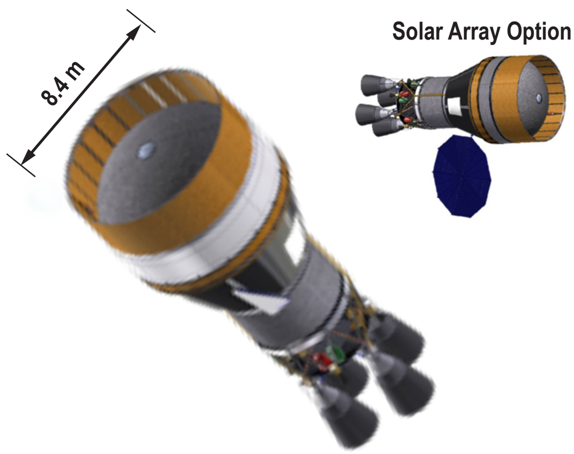
Figure 69. SLS Blocks 1, 1B, and 2B POD vehicle configurations.

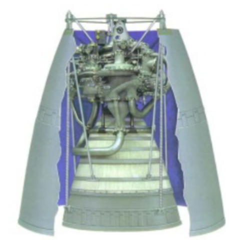
### 3.3 Space Launch System Blocks 1 and 2B Exploration Upper Stage

The current 27.6-ft (8.4-m) diameter × 60-ft-long stage EUS concept (fig. 70) was developed to provide both ascent/circularization and in-space functions. Powered by four RL-10C2 engines, it is capable of either single (ascent/circularization) or dual (ascent/in-space) function. Capable of being fueled with 275,600 lbm of propellant and with a dry mass of 33,800 lbm, it has a propellant mass fraction (pmf) of 0.89. Depending on EUS mission length, batteries and/or a deployable solar panel will provide power while a passive thermal control system minimizes cryogenic propellant boiloff. The inner loop (SLS program) accepted this basic configuration as Block 1B POD in May 2014 and is now actively developing it.




**Engine**

| | RL–10C2 |
|---|---|
| Nominal Vac Thrust (lbf) | 24,750 |
| Nom/Min Vac Isp (s) | 465/462 |
| Mixture Ratio (range capability) | 5.88 (none) |
| Mass (lbm) w/Extension | 668 |



**4× RL–10C2**

Figure 70. SLS EUS.

### 3.4 Space Launch System Blocks 1, 1B, and 2B Performance

Based on the introduction of the EUS into the SLS architecture, new performance curves were generated in the spring of 2014. The new payload delivery to Earth escape for a range of characteristic energy, or C3, for SLS Block 1 cargo and SLS Blocks 1B/2B configurations is given in figure 71.

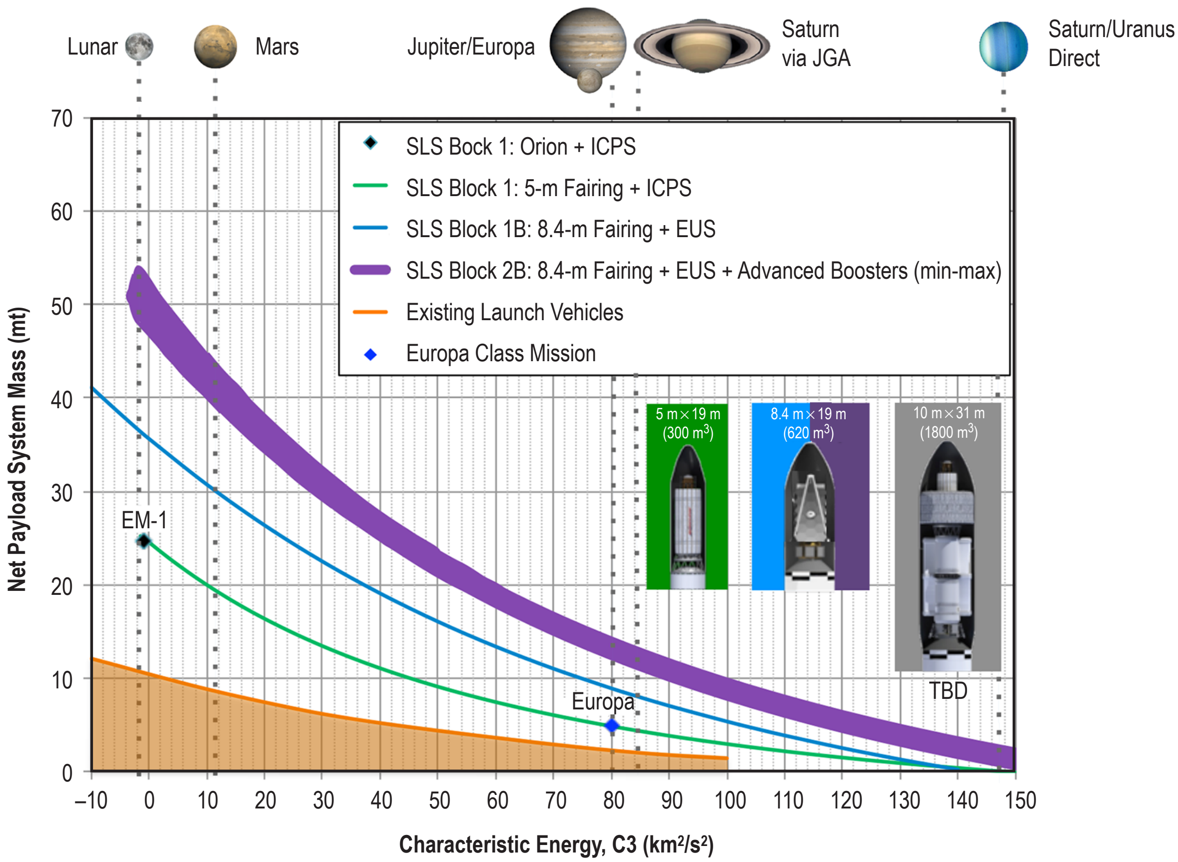



Figure 71. SLS Blocks 1, 1B, and 2B performance.

## 4. SUMMARY

The ADG's plans for FY 2015 are to continue the existing academia activities and some of the industry and ABEDRR tasks. The current in-house tasks will be reviewed, some will be continued, and new ones will be selected using the process described in Section 2.

The ADG portfolio of tasks covers a broad range of technical developmental activities supporting the evolution of the SLS vehicle. The tasks are structured to provide off-ramps on a yearly basis in event of budget constraints or lack of progress. A summary schedule of all the tasks is shown in figure 72. The summary budget was shown in section 1.6, table 2.

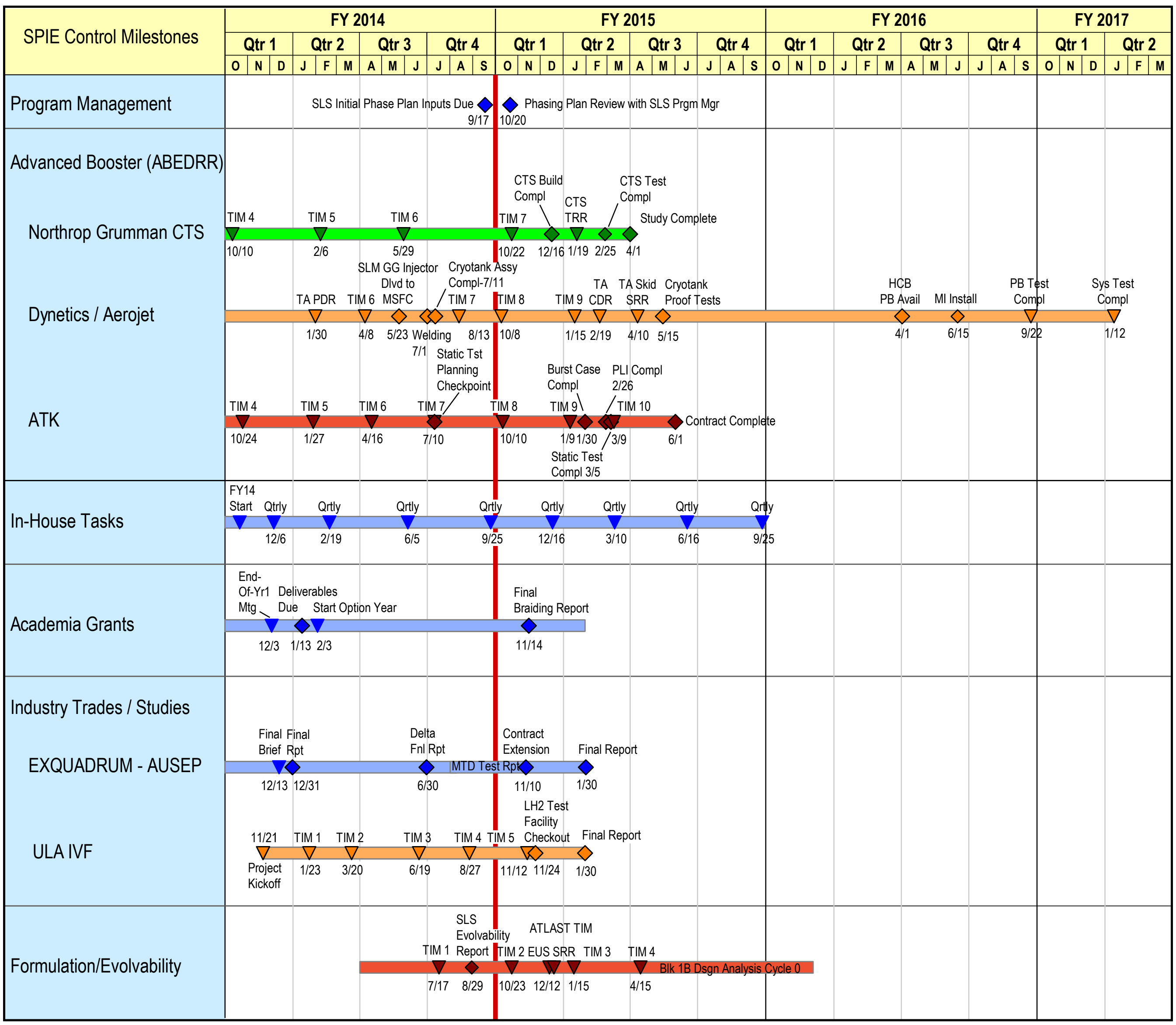



Figure 72. ADG summary schedule.

Through its broad portfolio of in-house activities and partnerships with academia and industry, the SLS ADO is laying the groundwork for the future evolution of the vehicle from its initial capability through its eventual development into the most capable launch vehicle ever flown (fig. 73). It will be able to carry astronauts on missions of exploration into the solar system and enable unprecedented scientific missions and other payloads. Engineering development and risk reduction work on advanced boosters during FY 2014 has already yielded not only a better understanding of potential booster concepts, but also has produced demonstration hardware that resulted in test firings. Concept studies on upper stage architecture and engines have opened new possibilities for greater and earlier mission capture as SLS evolves. Both in-house and academia research are producing results that will not only help make SLS a truly state-of-the-art vehicle, but could provide benefits for the American space industry as a whole.

Figure 73. SLS launch vehicle.

# APPENDIX—POINTS OF CONTACT

The points of contact are listed in table 3.

Table 3. Points of contact.

| Name | Responsibility | Phone | E-mail |
|---|---|---|---|
| Chris Crumbly | SPIE Manager | 265–544–1502 | chris.crumbly@nasa.gov |
| Steve Creech | SPIE Deputy Manager | 265–544–9365 | stephen.d.creech@nasa.gov |
| Fred Bickley | ADG Lead | 265–544–2370 | fred.p.bickley@nasa.gov |
| Keith Dill | SPIE Deputy Chief Engineer for Evolution | 265–544–1883 | keith.dill@nasa.gov |
| Mindy Nettles | Academia & NASA Tasks Manager | 265–544–1569 | melinda.nettles@nasa.gov |
| Brian Barley | Industry Tasks and ABEDRR—NGC COTR | 265–544–2992 | bryan.barley@nasa.gov |
| Angie Jackman | ABEDRR—ATK COTR | 265–544–0696 | angie.jackman@nasa.gov |
| Sam Stephens | ABEDRR—Aerojet & Dynetics COTR | 256–544–5244 | samuel.e.stephens@nasa.gov |
| Jon Holladay | Formulation/Evolvability Group Lead | 265–544–7250 | jon.holladay@nasa.gov |

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**14. ABSTRACT**
The Advanced Development Office (ADO), part of the Space Launch System (SLS) program, provides SLS with the advanced development needed to evolve the vehicle from an initial Block 1 payload capability of 70 metric tons (t) to an eventual capability Block 2 of 130 t, with intermediary evolution options possible. ADO takes existing technologies and matures them to the point that insertion into the mainline program minimizes risk. The ADO portfolio of tasks covers a broad range of technical developmental activities. The ADO portfolio supports the development of advanced boosters, upper stages, and other advanced development activities benefiting the SLS program. A total of 36 separate tasks were funded by ADO in FY 2014.

**15. SUBJECT TERMS**
advanced development, launch vehicle, NASA, Space Launch System, technology

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Space Administration
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**George C. Marshall Space Flight Center**
Huntsville, Alabama 35812